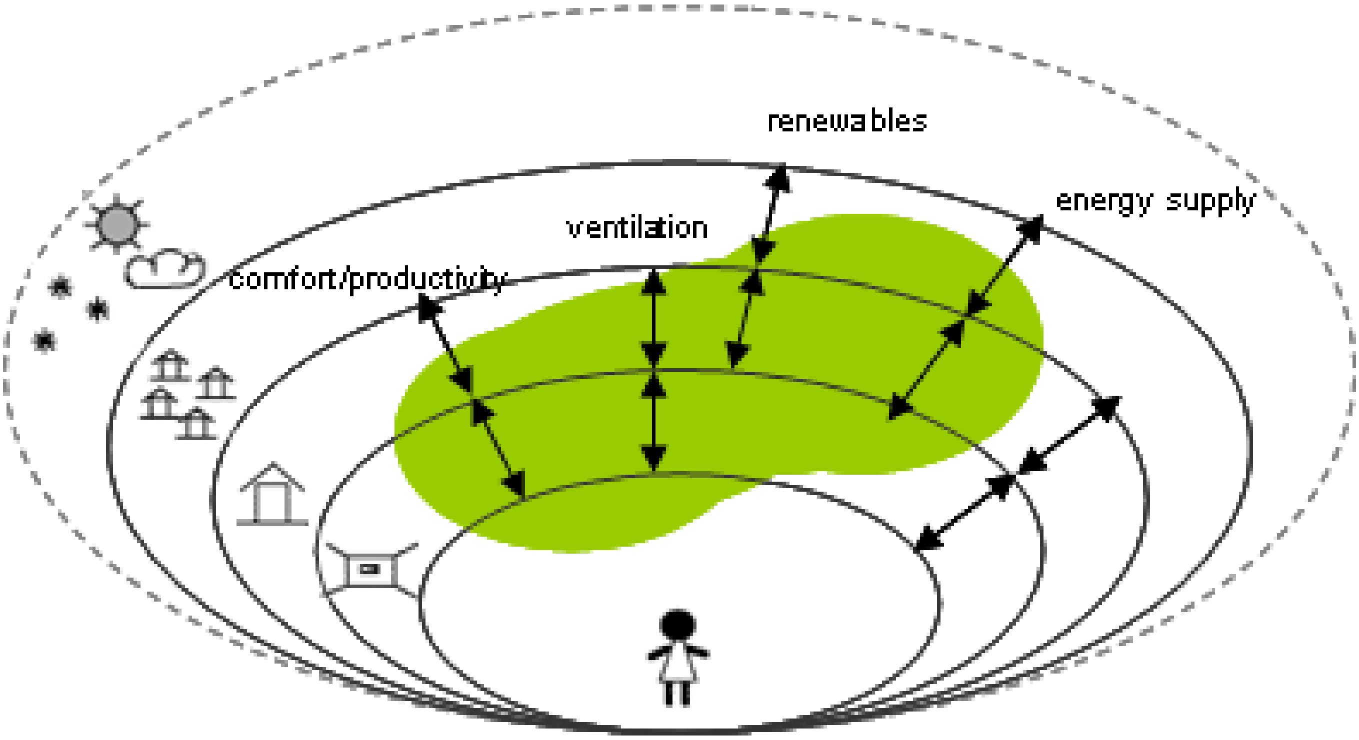
LOW-EXERGY IN THE BUILT ENVIRONMENT
INSIGHTS FROM THE COSTeXergy ACTION

Analysis and Design of Innovative Systems for Low-Exergy in the Built Environment



EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

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EUROPEAN COOPERATION
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ABOUT COST

COST (European Cooperation in Science and Technology) is Europe's longest-running intergovernmental framework for cooperation in science and technology funding cooperative scientific projects called 'COST Actions'. With a successful history of implementing scientific networking projects for over 40 years, COST offers scientists the opportunity to embark upon bottom-up, multidisciplinary and collaborative networks across all science and technology domains.

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Support to young researchers

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ABOUT THE COSTeXergy ACTION

The main objective of the CosteXergy Action was to broadly disseminate new knowledge and practical design-support instruments that can facilitate practical application of the exergy concept to the built environment.

In order to achieve this objective, the Action relied on research activities carried out by its members, which focus on investigating and demonstrating how exergy analysis can be used in the development of innovative insights and concepts and to support a wider deployment of low-valued heat and other renewable energy sources.

The Action focused on thermal energy in the built environment, mainly at the building and building component level.

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Preface

Elisa Boelman[1] and Hedzer Johannes van der Kooi[2]

[1]EU Committee of the Regions (in a personal capacity), formerly with the Delft University of Technology, Climate Design Group, The Netherlands

[2]Delft University of Technology, Faculty of Architecture, Climate Design Group, The Netherlands

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ABOUT THE COSTeXergy ACTION

Background

Energy for heating and cooling purposes amounts to more than 50% of the yearly energy demand of buildings in the operational phase. While high in terms of energy units, the heating needs of buildings can in principle be met by low-grade heat sources, since the required temperatures are usually below 100 ºC. However, high-temperature processes (e.g. fossil fuel combustion) are often used to deliver the low-grade heat required by end-users in buildings. Also, the temperature of heat delivery to indoor spaces (e.g. by radiating panels) is often higher than what would be required in terms of human thermal comfort and the rational use of renewable energy and passive strategies.

Nowadays, energy systems in buildings are designed based solely on the energy conservation principle. However, this principle alone does not provide a full understanding of important aspects of energy use in buildings, e.g. matching the quality levels of energy supply and end-use; describing how the human body experiences temperature differences between indoor air and surfaces (e.g. wall, ceilings, etc.); fully expressing the advantages of using passive (e.g. thermal insulation, window design) and ambient energy (e.g. heat pumps) in buildings.

The exergy analysis method is well known for optimisation of energy conversion in large industrial and power plants. It is also applied to quantify material flows (e.g. plastics, metals) involved in the manufacturing and recycling of industrial products (e.g. cars). However, it is not popular in the building sector, and needs to be adapted to the needs of the building profession.

Objective and focus

The main objective of the COSTeXergy Action was to broadly disseminate new knowledge and practical design-support instruments that can facilitate practical application of the exergy concept to the built environment.

In order to achieve this objective, the Action relied on research activities carried out by its members, which focus on investigating and demonstrating how exergy analysis can be used in the development of innovative insights and concepts and to support a wider deployment of low-valued heat and other renewable energy sources.

The Action focused on thermal energy in the built environment, mainly at the building and building component level.

Activities

The COSTeXergy Action enabled several international conferences, workshops, training schools and short term scientific missions on exergy in the built environment. The high involvement of young researchers is reflected in the contributions to this book: fifteen of the forty authors are early stage researchers, most of whom were working on their doctoral research during the Action. Five sections in this book (sections 1.3, 2.1, 3.4, 5.3 and 5.4) are the result of short term scientific missions carried out within the Action. Section 4.2 is the result of a workshop supported by the Action, and sections 5.2 to 5.7 benefitted from young researchers' participation in training schools supported by the Action.

http://www.costexergy.eu

ABOUT THIS BOOK

This book brings together papers written by young and senior researchers who contributed to the COSTeXergy Action through participation in and organization of training schools and short term scientific missions.
Authors and their contributions span a wide range of disciplines, from building and mechanical engineering to chemistry, thermal comfort and energy economics. This diversity is reflected in a rich variety of approaches and styles in a compilation of 27 papers on exergy in the built environment.
The individual papers are clustered into five chapters, introduced by chapter editors, dealing with: (1) exergy related definitions for the built environment; (2) methodologies and tools for exergy analysis of buildings; (3) exergy as a sustainability indicator; (4) innovative technologies, case studies; (5) methodologies and evaluation of human body exergy consumption.
While papers are ordered so as to provide a narrative within chapters, each of them can also be read autonomously.

Note for readers

This book endeavoured to provide as wide as feasible publication opportunities for active participants of the COSTeXergy action, and was edited on a voluntary basis. In spite of continued editing efforts, imperfections may still remain in terms of accurate and consistent definitions/terminology, text, referencing style, use/documentation of symbols in equations and symbol lists, substantiation of thermophysical properties and other numerical values, etc.
Imperfections notwithstanding, the editors believe that novel insights presented in this book could inspire other researchers to pursue work on exergy in the built environment and consolidate the pioneering work presented by young and senior researchers in this book.

Acknowledgement

Support by COST enabled the research networking activities that led to this book, and is gratefully acknowledged.

Exergy and sustainability vademecum

Hedzer Johannes van der Kooi

Delft University of Technology, Faculty of Architecture, Climate Design Group, The Netherlands

This vademecum briefly reviews some of the main underlying concepts related to exergy and sustainability, as approached by most authors in this book. Such concepts, which should always be the starting point of exergy-based analysis and design, are often taken as underlying postulates without always being explicitly asserted.

This vademecum, at the very start of the book, is meant as a source of reflection and inspiration for building professionals interested in applying exergy and sustainability philosophies to their analyses and designs.

The exergy concept

- in all processes energy is ‘conserved’, only transitions from one form of energy into another are possible. However, exergy is not conserved but decreases with every transition.
- exergy is equivalent to work. Also, all forms of work are equivalent to exergy.
- the exergy of thermal energy is usually not equivalent to work.
- exergy is the maximum amount of work obtainable from a non-equilibrium state.
- that part of the exergy of a system with pressure and temperature differing from its standard pressure and temperature, solely related to these differences, is called the physical or thermo-mechanical part of the exergy of that system.
- exergy values of materials can be considered to be composed of a physical and a chemical part. The chemical contribution is determined with respect to the lowest exergy state - the absolute equilibrium state - of the actual environment.
- exergy values are expressed in J.

Exergy losses and reversibility

- there is a direct relation between exergy losses and entropy generation.
- exergy is irretrievably lost.
- exergy losses are a consequence of the finite driving forces necessary for the processes to take place in the direction wanted. The losses are proportional to the sum of the products of these independent driving forces and their related streams.
- in the limiting ideal case, when there is no friction and the driving forces decrease to zero, there are no exergy losses, and we speak about reversible processes.
- comparing real processes to their reversible limits reveals how close the real processes are to their reversible limit, and hence whether there is room for improving the process (or whether further improvements require shifting to a different process).

Entropy

- in all real processes entropy generation (exergy losses) take(s) place.
- entropy generation is equal to the sum of the products of the independent driving forces and their related streams. This means that the streams and their related driving forces cannot be defined completely independent from each other. The products must have the unit W/K. For example, when a temperature difference is defined to be the driving force for the transfer of thermal energy than the related stream must be expressed in the unit W/K^2.

From fossil to solar

- today's main exergy source has a fossil origin. The use of fossil fuels is directly related to negative interactions with the environment. To be able to apply the necessary driving forces, fossil fuels are combusted. This nearly always contributes to increasing the environment's amount of carbon dioxide.
- when using solar exergy, the negative effects related to fossil fuels can be avoided. A good example is photosynthesis: in green plants solar exergy is used to make electrons available to produce NADH, which is a large organic molecule, from water while oxygen is released. In one of the following steps carbon dioxide is partially reduced by the active hydrogen atom of NADH, and finally glucose is produced. The glucose functions as an exergy source to drive the production of nearly all biomass.
- it is biomass, produced from photosynthesis, which has it made possible for fossil fuels to be formed over the course of long periods.

Exergy in a sustainable future

- in a sustainable future, biodiversity must be maintained or possibly be increased. Solar exergy is necessary for the biosphere/ (hydrosphere) and processes taking place in the technosphere (understood to be the part of the physical environment affected through building or modification by humans[1]). Because of this, its use in the technosphere must be reduced as much as possible. The same goes for the exergy losses related to processes such as heating and cooling.
- solar radiation must be the exergy source to drive the processes in the technosphere in a way comparable to photosynthesis in green plants.
- these processes must be performed in such a way that the exergy losses are as small as reasonably possible.
- the activities in the technosphere must meet several boundary conditions:
    - bio diversity must be maintained and possibly increased.
    - the natural cycles must not be disturbed.
    - elements, not taking part in natural cycles, are not allowed to be released into the biosphere. These elements must be recycled in the technosphere.
    - only those substances are allowed to be released in the biosphere that do not over burden the natural cycles or belong to the substances present in the soil. In this last case, they can be returned to the soil when they do not have negative effects on biodiversity and maintain, or possibly increase the quality of the soil (eventually after proper mixing).

[1] http://encyclopedia2.thefreedictionary.com/technosphere

- degraded substances are not allowed to be released in the biosphere when causing negative effects or when these effects are not known.
- all substances not allowed to be released in the biosphere must remain in the technosphere.
- only those products may be produced in the technosphere that can be maintained, repaired and reused with a small exergy input, and have no negative effects in the biosphere.
- these products must be assembled, and finally disassembled, and reused in such a way that only a small exergy input is necessary.
- lastly, when the products themselves cannot be recycled, their constituents, or when necessary other substances produced there from, must be recycled in the technosphere.

The best low-exergy systems in buildings are those which only use exergy sources containing a small fraction of the energy input as exergy, such as thermal energy at near-environmental temperature. Furthermore, the exergy losses must be as small as reasonably possible.

Sustainability in the ecosphere and technosphere

The above section outlines key exergy concepts in relation to sustainability. This section briefly discusses exergy in relation to life on earth and also as a driving force that can be used to drive design and production processes in desired directions. Section 3.2 delves into technological aspects of sustainability and parameters to express those aspects. Ecosphere is understood to be the regions of the Earth that are capable of supporting life, together with the ecosystems they contain; the biosphere[2].

What can we learn from life processes on earth?

Life on earth can be considered as a dynamical system, open for input of solar radiation and for output of radiation with a smaller exergy content than that of the incoming radiation. This solar exergy is by far the most important exergy source used to make life on earth possible. In the photosynthesis process, taking place in green plants, carbon dioxide and water are converted into carbohydrates and into oxygen that is released to the atmosphere. By internal combustion of these carbohydrates, exergy becomes available in the form of the exergy carrier adenosine triphosphate (ATP). This exergy carrier is then used to produce all other substances occurring in living cells, e.g. proteins. For these processes, minerals are also necessary. These are extracted from water or from soil where the plants grow. From a recent study by Lems (2009[3]) it is clear that the exergy efficiency of the cellular processes investigated was much higher than in our technical chemical conversions, with the exception of those process steps where process regulation takes place, and of the first steps of the photosynthesis process.

Glucose (a carbohydrate) breakdown in primary cells to produce the exergy carrier ATP is an example of breakdown and build- up of substances directly related to each other (in this case so called coupled chemical reactions). Building up and breaking down of organisms is characteristic for the cycle of life on earth. In nature, plants are eaten by animals to provide them with exergy and substances they are unable to produce themselves. The animals on top of the food chain feed only on other animals. After death, mainly bacteria and moulds use the dead material as exergy source to drive their own life processes. In this way, minerals are returned to the soil, and e.g. carbohydrates are broken down into water and carbon dioxide, from which they were originally produced.

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[2] http://www.thefreedictionary.com/ecosphere

[3] Lems S. 2009. *Thermodynamic Explorations into Sustainable Energy Conversion. Learning from Living Systems*, Thesis, Delft University of Technology.

The closure of cycles, e.g. the carbon cycle, is also directly related to life. Carbon dioxide is taken up from the atmosphere and the hydrosphere and is finally released there again. Our fossil fuels are formed from plants and/or animals by means of geological processes, at much higher pressures and temperatures than on the surface of the earth. Combustion of fossil fuels leads, among others, to carbon dioxide formation, which overburdens the natural carbon cycle. The carbon dioxide is emitted to the atmosphere and partly dissolves in water where calcium hydrogen-carbonate and calcium carbonate are formed. Our green plants are not able to fixate this carbon in biomass at such a speed that the carbon dioxide concentration in the atmosphere would remain constant. This is why the carbon dioxide concentration increases in the atmosphere and the calcium level in the sea decreases. This leads to negative effects in living systems and to a decrease in biodiversity. From what we have seen we must conclude that the use of fossil fuels must be reduced as fast as possible. Not only the use of fossil fuels, but also many of our material processes have negative effects on biodiversity. In a sustainable society, these negative effects are not longer allowed. Allowable emissions to the ecosphere are only those that do not overburden the natural cycles, or that can lead to an increase of biodiversity. Other emissions must be treated in such a way that the substances present remain in the technosphere, and are available for the material conversions in the technosphere.

Technological aspects of sustainability

Based on the previous discussion we have seen that our processes must make use of an exergy source to be able to apply the appropriate driving forces in the wanted direction. These driving forces lead to related streams, which are normally the goals to achieve in the design and realization of production, construction and operation processes.

The main characteristics of the technological aspects of sustainability are a direct consequence of the following observations:

- The main exergy sources used in the technosphere are of fossil origin and are normally not directly available. They are present in the upper part of the crust of the earth, and must be prospected before being explored, produced and processed and used This leads to emissions to the ecosphere, the hydrosphere and the atmosphere, overburdening natural cycles and drastically decreasing biodiversity.
- The exergy source available on earth and not directly leading to the transfer of substances buried in the crust of the earth to atmosphere, hydrosphere and ecosphere is solar exergy. We have seen that solar exergy is used to make nearly all life processes on earth possible.
- This means that we must make use of solar exergy in a sophisticated manner. Biodiversity must be maintained and we must assure that harvesting solar exergy is done in such a way that the optical characteristics of the surfaces used is as much the same before as after their use in the harvesting process.
- We must think e.g. of the use of building surfaces for this harvesting process in our technosphere. The current production of silicon-based photovoltaic cells (PV) relies on processes which not only produce the PV cells but also lead to emissions and to the formation of by products. Mimicking the first steps in the photosynthesis process could circumvent these problems.
- The use of solar radiation leads to the necessity of carefully using our exergy sources and hence to the necessity to reduce exergy losses in our processes as much as possible.
- Reuse of materials applied in products must be as easy as possible and the materials from which the products are made of must be chosen such that they can be reused with the smallest amount of exergy input. This means that the products must be designed and produced in such a way that they can be repaired, maintained, and reused making use of a small exergy input.

- Furthermore, the largest part of sustainability must be realised already on a small scale, e.g. at the farm in the case of biomass, so that community-scale production helps to avoid long-distance transportation of all kinds of substances and the release of minerals at completely other places than where the biomass was grown. This is only possible when materials are reused on these scales too.
- The interaction between technosphere and biosphere must take place in such a way that biodiversity is maintained and possibly increased. This means that harmful or toxic substances (or substances of yet-unknown harm or toxicity) should not be allowed to be produced, used and certainly not emitted to the biosphere. When these substances are used in the technosphere they must be handled with care and should not be allowed to come into the biosphere – even not via processes such as wear, corrosion etc., related to their use.

CHAPTER 1

EXERGY RELATED DEFINITIONS FOR THE BUILT ENVIRONMENT

Introduction

Mia Ala-Juusela

VTT Technical Research Centre of Finland

The LowEx approach helps to better match energy demand and supply, not just in terms of quantity but also of quality, and hence to improve the overall effectiveness of energy resource utilisation. The LowEx approach favours systems that minimise thermodynamic losses, for example by operating as close as possible to the surrounding environment conditions and using ambient energy sources whenever possible, or by cascading the use of more energy-intensive energy resources. Exergy-related definitions and metrics often have their origin in other disciplines, e.g. mechanical and chemical engineering, and therefore it is not always straight-forward to apply them to the built environment. On the road towards high-performance LowEx built environments, it is important to understand the possibilities and limitations of applying relevant definitions and metrics.

In the first section of this chapter Shukuya outlines the applicability of the “exergy” concept to the built environment, in order to develop new insights into the development of future heating and cooling systems. The fundamental laws of thermodynamics are briefly reviewed, focusing on the derivation of the exergy concept, and then some of the findings are discussed from recent exergy research focusing on the built environment. The conclusions are that 1) any system, from heating to lighting to the human-body, works as an “exergy-entropy” process; 2) thermal exergy consists of both warm and cool exergies; 3) the lowest human-body exergy consumption rate in the winter season corresponds to relatively high mean radiant temperatures and relatively low air temperatures; 4) in summer, conversely, availability of cool radiant exergy seems to be very important for naturally-ventilated rooms.

In the second section, van der Kooi briefly reviews some of the thermodynamic fundamentals related to the definition and calculations of exergy. This entails the essence of energy, entropy and entropy generation, leading to a more generally applicable concept of exergy. An example is provided to clarify the relevant driving forces and their related streams.

Torio et al. reviewed a wide selection of papers handling exergy analysis of renewable energy based climatisation systems for the built environment. In the third section of this chapter they note that a common framework is missing for exergy analysis of systems covering several buildings. In exergy analysis it is particularly important to clearly state the system boundaries and accurately describe the energy processes, due to their major influence on results and conclusions. The authors also note that energy and exergy analyses can sometimes provide contradictory results, and that a methodology to combine results from these analyses should be elaborated. As renewable energy sources are not necessarily LowEx sources, further consideration and debate is needed on what is the final objective in the energy system design: to save primary energy or to save primary exergy.

The Zero-Energy Building (ZEB) approach aims at significantly reducing the quantity of energy required to operate a building, while using renewable energy sources to meet or exceed the remaining demand. ZEB is not explicit about the quality of energy, nor about an unequivocal set of parameters applicable to a wide range of climatic conditions and building practices. The definitions of Zero Energy Buildings (ZEB) and their benefits and limitations are considered by Rybka et al. in the fourth section of this chapter. There are different definitions of ZEBs, depending on the country, geographic situation, weather conditions and measuring methods. A ZEB produces at least as much energy as it consumes on an annual basis, with zero carbon emissions annually. This design principle is gaining interest as renewable energy is an important way to cut greenhouse gas emissions. ZEB is also one promising path towards LowEx communities, as they are capable of reducing the exergy demand of buildings significantly.

The next section presents and discusses exergy-related definitions and approaches relevant to the built environment. It attempts to relate paradigms from different professions, traditionally focused on demand (e.g. building science), supply (e.g. mechanical engineering) or resources (e.g. industrial ecology, chemical engineering). From an energy supply perspective, it is important to maximize the output obtained from a given input of resource, for example by improving the efficiency of a given process and/or by switching to inherently more efficient processes. Maximum theoretical efficiencies and improvement potentials based on the second law of thermodynamics are useful decision-support indicators for choosing between improving or reengineering processes. From a resource preservation perspective, it is advisable to design and operate buildings so as to first reduce the energy loads as much as possible and only use external energy resources (including the surrounding environment) for those energy loads that cannot be met otherwise. IEA ECBCS Annex 49 collected and assessed different definitions related to the exergy concept, and proposed a working definition of LowEx systems for buildings and communities. The results of this work are summarised by Boelman in the fifth section of this chapter.

Exergy calculation methods rely on several properties of the reference environment, like temperature, pressure and chemical composition. However, most calculations related to exergy and buildings only take into account the thermal exergy of air, without regard to chemical exergy (caused by differences in water-vapour content between indoor and outdoor air) or to mechanical exergy (caused by pressure differences between indoor and outdoor air). This may entail considerable inaccuracy, for example when dealing with humid climates. To assess the consequences and to give building professionals tools to quantify the exergy content of moist air, van der Kooi et al. present a detailed and complete derivation of equations for calculating the exergy value of air in buildings. The equations presented in the last section of this chapter consider the thermal, mechanical and chemical contributions. The writers conclude that due to the relatively large influence of the actual environment on the calculation of the exergy value of air in the building, it is necessary to consider not standard reference values but the actual environment as reference environment.

1.1 Comfortable High-Performance and Low-Exergy Built Environment

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1.1.1 Introduction

People often claim that energy is consumed. This is not only assumed in everyday conversation but also in scientific discussion associated with so-called energy and environmental issues. This claim, however, conflicts with the first law of thermodynamics stating that the total amount of energy is conserved even though forms of energy may change from one to another. All macroscopic natural phenomena happening around us involve the dispersion of energy and matter, which in due course change their form from one to another, but the total amount of energy and matter involved is never consumed but necessarily conserved.

When we use such expressions as “energy consumption”, “energy saving” and even “energy conservation”, we implicitly refer to “energy” as intense energy available from fossil fuels or from condensed uranium. But, it is confusing to use one of the most well-established scientific terms, energy, to mean “to be conserved” and “to be consumed” simultaneously. This is why we need to use one of the thermodynamic concepts, exergy, intensively and extensively to articulate what is consumed.

In this paper, we briefly review the fundamental laws of thermodynamics aimed at the derivation of the exergy concept and then discuss some of the findings obtained from recent exergy research focusing on the built environment.

1.1.2 Exergy-Entropy Process

Let us first discuss using a simple imaginary heat engine working under a steady-state condition as schematically shown in the left-hand side of Figure 1. We first set up its energy balance equation according to the “energy conservation law”. The inflow of energy equals the sum of the outflows of energy. The heat engine works in the dispersing flow of energy, namely “heat”, from the hot source to the cold source. Thereby it extracts the non-dispersing flow of energy, namely “work”.

Whenever the heat engine produces work, some positive value of entropy is necessarily generated. With this in mind, we can set up the entropy balance equation that is consistent with the energy balance equation. The limiting condition of the heat engine which does not generate even the slightest amount of entropy is that it is operated with infinitely-slow motion. A heat engine under such conditions is not useful at all. Therefore, useful heat engines generate some amount of entropy.

A unique aspect of the entropy balance equation is that there exists a term "entropy generation". The sum of the entropy flowing into the system and the generated entropy within it, equals the out-flowing entropy. This implies that the generated entropy is discarded.

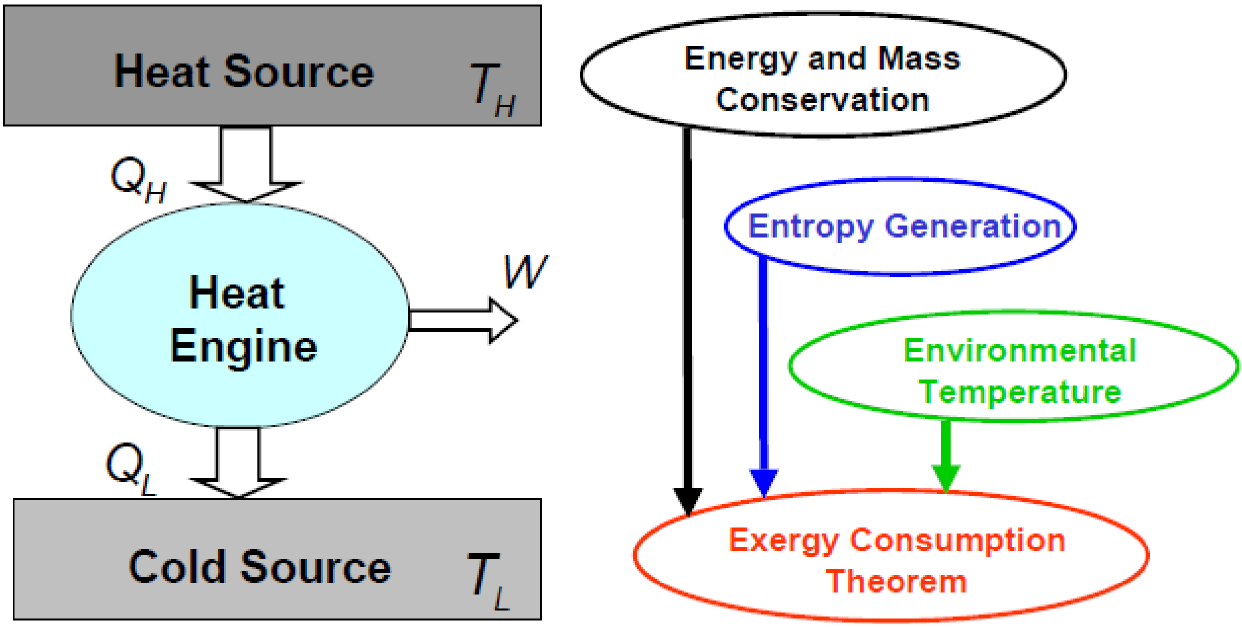

Figure 1: An imaginary heat engine working with the heat source whose temperature is constant at T_H and with the cold source (heat sink) whose temperature is constant at T_L. The engine extracts an amount of work, W, which is not yet dispersed, through the two dispersing flows of thermal energy, Q_H and Q_L, from the heat source to the cold source.

The concept of entropy can be regarded to be a measure to quantify to what degree an amount of energy or matter is dispersed or how much the dispersion occurs. "Heat" is energy transfer by dispersion due to conduction, convection or radiation, sometimes together with mass diffusion, namely evaporation. On the other hand, "work" is energy transfer not by dispersion: work is performed by a directional (parallel) movement of particles of a substance that has a certain shape or form as solid. Energy transfer by heat is necessarily accompanied by entropy transfer and entropy generation, while energy transfer by work only is accompanied by no entropy transfer.

Generally speaking, energy contained by a body, which has the ability to disperse, is called an energy source. Such an energy source exists within the environmental space, which is filled with dispersed energy. Therefore the cold source shown in Figure 1 can be regarded as the environmental space for the heat source and for the heat engine. Since the concept of entropy is, as mentioned above, a measure to quantify the degree of dispersion and its unit is J/K (W/K for the rate), the dispersed energy level of the heat source surrounded by the environmental space can be expressed as the product of entropy contained by the source and its environmental temperature on a Kelvin scale. The product of entropy and environmental temperature is called “anergy”, which implies dispersed energy; the unit of both energy and anergy is J (W for the rate).

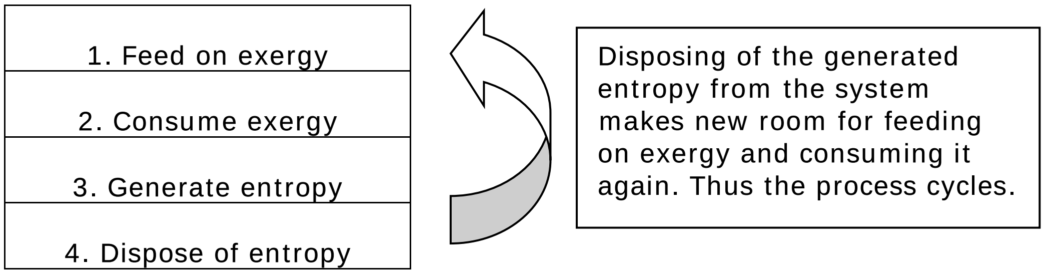

Figure 2: Exergy-entropy process

A portion of energy to be expressed as the difference between total energy and its dispersed portion, anergy, is the amount of energy which has an ability to disperse. This is exactly the concept of “exergy”. The exergy balance equation is therefore obtained from the two balance equations in terms of energy and entropy together with the concept of “environmental temperature”.

Another unique point of the exergy balance equation is that there exists a term “exergy consumption”. This implies that a portion of exergy supplied from the source flowing into the system is necessarily consumed (destroyed) and thereby an amount of work, which is exergy itself, is extracted.

The heat engine must be operated cyclically to produce the work continuously – i.e. to be useful. To realize this cycle, it is essential for the engine to continuously dispose of the generated entropy so that its state, expressed by temperature and pressure, remains unchanged. The entropy contained by a certain body is a function of the body temperature and pressure. A general characteristic is that the value of entropy increases as the body temperature rises or as the body pressure decreases (the volume increases).

In order to keep the state of the engine unchanged, it is necessary for the system to dispose of the generated entropy. We call the process described above “exergy-entropy” process. Figure 2 shows the four fundamental steps of the exergy-entropy process. Any working system cyclically performs these four consecutive steps. The built-environmental systems such as heating, cooling, or lighting systems and also human-body systems are no exceptions (Shukuya 1994; 2004).

1.1.3 Exergetic view of the built environment

Warm and Cool Exergies

The amount of exergy contained by a substance varies with its temperature and also with the environmental temperature. Figure 3 shows an example of thermal exergy contained by 81 m^3 (6m x 5m x 2.7m), a room size, of air as a function of its temperature at an environmental temperature of 288 K (=15 °C). It should be noted that air has a certain amount of exergy both when the air temperature is higher than the environment and when the air temperature is lower than the environment (Shukuya and Hammache 2002).

The exergy contained by air at a temperature higher than its environment is an ability of thermal energy contained by the air to disperse into the environment. On the other hand, the exergy contained at a temperature lower than its environment is an ability of the air, in which there is a lack of thermal energy compared to the environment, to let the thermal energy in the environment flow into it. We call the former “warm” exergy and the latter “cool” exergy (Shukuya, 1996).

Either “warm” exergy or “cool” exergy described above is a quantity of state contained by a substance relative to its environment. When a room space is heated, we have a room temperature higher than the outdoor environment. In such a case the room air has “warm” exergy as a quantity of state. On the other hand, when the room space is cooled, we have a room temperature lower than the outdoor environment. In this case, room air has “cool” exergy as a quantity of state.

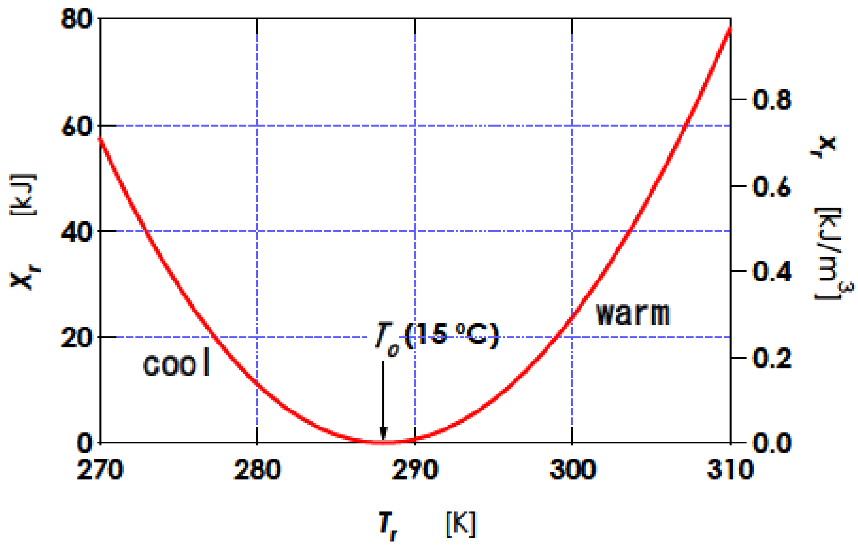

Figure 3: Thermal exergy contained by air, X_r as a function of temperature, T_r. The unit of thermal exergy, X_r, is kJ. Air volume is assumed to be 81 m^3 (6m x 5m x 2.7m). Environmental temperature, T_o, is 288 K (=15 °C).

The function of heating systems is to supply and consume exergy in order to maintain the “warm” exergy contained by room space at a desired level. Cooling systems, on the other hand, are the systems that supply and consume exergy in order to maintain the “cool” exergy contained by room space at a desired level. The exergy supply is a process whereby exergy is transferred either by flows of conduction, convection, or radiation.

Human-body Exergy Consumption Rate and Thermal Comfort in Winter

Biological systems including the human body also work as a heat engine. So called metabolism is another expression of the exergy-entropy process. Whether one can feel thermally comfortable or uncomfortable in a room space is related to how much of warm exergy is consumed within the human body. Figure 4 shows an example of such a relationship in winter conditions, obtained from a human thermoregulatory system analysis from the exergetic viewpoint (Isawa et al. 2002; 2003).

The horizontal axis represents air temperature and the vertical axis shows mean radiant temperature surrounding a human body. Mean radiant temperature is the average of internal surface temperatures of building windows, walls, floor, and ceiling. The fine lines with numbers are equi-exergy-consumption-rate lines within a human body. The bold line going from upper-left down to lower-right corresponds to the state of the human body whose metabolic energy emission rate equals the energy outflow due to radiation, convection, evaporation, and conduction.

According to the previous knowledge of human thermal physiology, a condition in which overall energy outflow from the human-body surface equals the metabolic energy emission rate provides the human body with thermal comfort. In other words, any set of room air temperature and mean radiant temperature on the bold line in Figure 4 provides a comfortable indoor thermal condition. Nevertheless, according to experienced architects and engineers concerned with designing comfortable built environments, a set of relatively high mean radiant temperatures and relatively low air temperatures brings about a better indoor thermal quality in winter season. This corresponds very well to an indoor condition that brings about the lowest exergy consumption rate within the human body as shown in Figure 4.

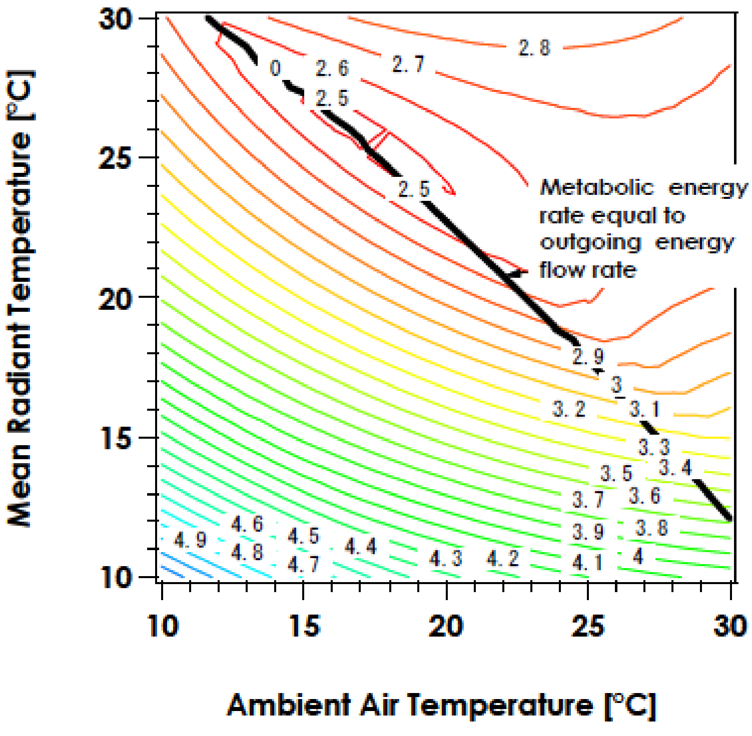

Figure 4. Relationships between human-body exergy consumption rate, whose unit is W/m^2 (body surface), and its environmental temperature under a winter condition (0ºC; 40%rh). There is a set of room air temperature (18 to 20 ºC) and mean radiant temperature (23 to 25 ºC) which provides the human body with the lowest exergy consumption rate.

These results suggest that human body as a biological system has evolved over the years, since the birth of life on the globe so that we humans feel most comfortable with the lowest exergy consumption rate, at least in winter conditions.

Cool and Warm Radiant Exergies and Thermal Comfort in Summer

A chart similar to Figure 4 can be made for the outdoor environmental condition for summer season. The values are different, but also in this case the lowest human-body exergy consumption rate coincides with a combination of high mean radiant temperature and a low air temperature. This seems consistent with what has been so far aimed at in case of conventional convective cooling.

In the case of natural cooling, a good combination of nocturnal natural ventilation, external solar shading and an appropriate amount of internal thermal mass, provides indoor conditions of a little lower mean radiant temperature and higher air temperature during daytime. This is comfortable enough, especially in residential buildings. Figure 5 shows an experimental example of the relationship between the percentage of comfort votes and warm/cool radiant exergies available in a naturally ventilated room. The subjects in this experiment perceived no air current, although windows were opened to allow for cross ventilation, there was little outdoor wind. Results were obtained from an in-situ experiment made in two small wooden buildings with natural ventilation in summer (Shukuya et al. 2006).

The closed circles "•", in figure 5, denote the cases that cool radiant exergy is available and the open circles "○" denote warm radiant exergy. As the warm radiant exergy rate grows, the percentage of subjects voting for comfort decreases. If the warm radiant exergy flow rate reaches 20 mW/m^2, no subjects vote for comfort. On the other hand, the same rate of "cool" radiant exergy results in the opposite condition in which most of the subjects do vote for comfort. Cool radiant exergy of 20 mW/m^2 is available, provided that the mean radiant temperature is lowered slightly compared to the outdoor air temperature.

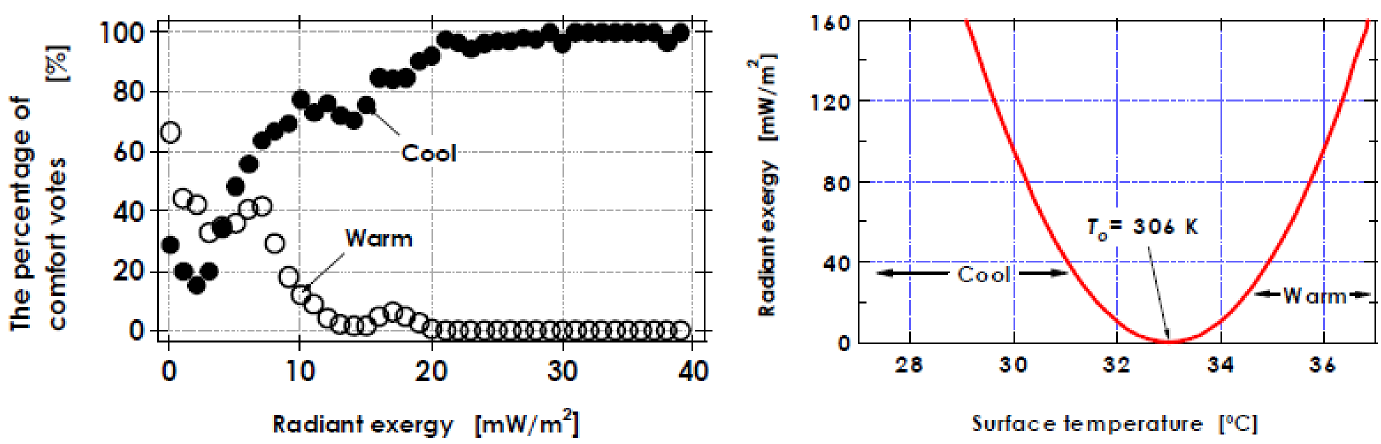

Figure 5. The percentage of the comfort votes under the condition of no perceived air current as a function of radiant exergy emitted from interior wall surfaces (see the chart on the left). Warm and cool radiant exergies are both in the range of 0 to 100 mW/m^2 (see the chart on the right). The results are for summer conditions

This result confirms that the use of external solar shading is the first priority in order to make a comfortable built environmental condition in summer with natural ventilation. The use of external solar shading devices together with nocturnal ventilation and the use of moderate thermal mass of floors and walls enable the production of cool radiant exergy during the daytime in summer. There are several existing buildings with internal solar shading instead of external shading. The built environment in those buildings, in summer, behaves as if it were being heated by the internal solar shading devices serving in this case as radiant heating panels. This in turn requires lower air temperature for cooling.

1.1.4 Concluding Remarks

Exergy consumption is always accompanied with entropy generation, thus the generated entropy must be constantly discarded from the room space to the outdoor environment to keep the “warm” or “cool” exergy within a desired level. A challenge is to seek a design solution that works with the smallest amount of exergy supply possible, while at the same time producing the required exergy from the immediate outdoor environment and making its smart use to get a certain level of well-being in the built-environmental space.

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1.2 Thermodynamic concepts – brief review

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1.2.1 Introduction

This section briefly reviews some of the thermodynamic fundamentals related to the definition and calculations of exergy. It uses mainly descriptive language and endeavours to keep equations as simple as possible. For those readers more familiar with thermodynamics, this section also includes a few inserts (framed text, in italics) with more details. The definitions presented in chapter 1, and the methodologies and tools described in chapter 2 further elaborate on concepts and formulations required in applications specific to the built environment.

1.2.2 Energy

We think to have a good understanding of concept of energy, but it is necessary to go into more detail. The first law of thermodynamics states that energy is conserved and thus it can neither be created nor destroyed; this is often expressed as: the total amount of energy in the universe remains constant.

The best idea about energy is obtained from the following definition: The total amount of mechanical energy W of a solid body upon which a sole constant force F acts, through its centre of gravity, leads to a displacement in the direction of the force over a distance l, and when we assume that no friction of the body with its surroundings occurs, this total amount of mechanical energy done on the body is defined as:

$$W = \int_l F * \cos(\varphi) * dl \qquad (1)$$

φ is the smallest angle between the direction of the force F and the displacement dl.

There are many kinds of mechanical energy. For example: potential energy, kinetic energy, rotation energy, elastic energy, surface energy and electrical energy. We know that when we are biking, we have to turn the pedals around, performing work, to go from one place to another. On a flat road without friction, an impulse would have been sufficient to get the bicycle moving and the work done to generate this impulse could have been recovered by appropriate means. In reality friction occurs, e.g. in the power transferring mechanical systems, with the road, and with the surrounding air. This friction leads to conversion of (part of) the mechanical energy into thermal energy.

Thermal energy (heat) is another form of energy that is, for example, transferred to the surroundings of the solid body due to friction of that body in the surface of contact with its environment (see also the example of the bicycle).

From experiments follows that when different forms of energy (e.g. mechanical and thermal) are expressed in different units, as was originally done, that one always finds a constant factor as the quotient of the total amount of mechanical energy when this is completely converted in thermal energy due to friction. This means that, when the same units are used to express both quantities of energy, these amounts of energy are the same. From this one can conclude that these two forms of energy are equivalent.

In general, it can be shown that all known forms of energy are equivalent. As a consequence, all forms of energy can be expressed in the same unit. In the SI system this unit is 'Joule' indicated with the symbol: 'J'. Experiments show that thermal energy cannot be transferred into mechanical energy completely when no forces act on our system, and when no changes occur in system and/or surroundings of the system. Another important observation is that when an amount of thermal energy Q is abstracted from a very large amount of thermal energy at a temperature T_h, such that this temperature remains constant, and when this temperature is higher than the temperature T_0 of the surroundings of our system, the maximum amount of work obtainable from Q, with respect to the surroundings of our system, can be calculated from the following relation:

$$W = Q\left(1 - \frac{T_0}{T_h}\right) \tag{2}$$

In the abstraction process, only thermal energy is abstracted from the large amount of thermal energy and transferred to the surroundings of our system at the temperature T_0 while an amount of work W is done on the surroundings. We obtain the maximum amount of work because the process is reversible. This process is called the Carnot process.

When the temperature $T_h < T_0$, this situation can only be obtained and maintained by cooling the system considered. In this case we will replace T_h by T_c to indicate that this temperature is smaller than the temperature of the environment. If an amount of cold is available, the maximum amount of work that can be obtained is given by equation (3)[1]:

$$W = Q\left(\frac{T_0}{T_c} - 1\right) \tag{3}$$

Equation (2) shows that when $T_h = T_0$, $W = 0$. No work can be obtained from thermal energy at its temperature T_0. The following is a mathematical limit:

[1] It is noted that equation (3) is valid when regarding the available cold as a positive value. More explanation on the exergy of cold can be found in Jansen and Woudstra, 2010.

$$\lim_{T_h \to \infty} W = \lim_{T_h \to \infty} \left(Q \left(1 - \frac{T_0}{T_h} \right) \right) = Q \tag{4}$$

In this limit, the amount of work done by the system is equal to the amount of thermal energy abstracted from a very large amount of thermal energy at an infinitely high temperature. As said, this is only a mathematical limit because our system can no longer be the same. When the temperature increases, the system considered is no longer stable: chemical bonds are broken, electrons are released, the nucleus dissociates, the nuclear particles dissociate etc.

From the discussion above, one can see that thermal energy and mechanical energy are not completely equivalent. All forms of mechanical energy can be completely converted into each other when no friction occurs. One can now say that thermal energy occurs as one of the possible forms of energy when friction occurs. Thus, it is clear that the total amount of mechanical energy after friction, is less than the amount of mechanical energy before the process took place. One can say that that part of the mechanical energy is irreversibly lost. Mechanical energy is related to the movement of molecules, from which the system is built up, in the direction of the force acting on the system. Thermal energy, however, is directly related to movement of the molecules also in other directions, and, depending on the system, finally in complete random movement of the molecules.

*The **first law of thermodynamics** can be written in the following balance equation for a volume element:*

$$\frac{dU + pdV + \sum_j \partial E_j}{dt} = \sum_k \dot{m}_k * h_k + \sum_j \dot{E}_j + \sum_l \int_{Q_l} \partial \dot{Q}_l + \sum_m \dot{W}_m \tag{5}$$

where U is the internal energy and V is the volume of the volume element considered. This volume element can also undergo changes in different forms of mechanical energy j. This is represented by the contribution: $\sum_j \delta E_j$ *.*

The first sum on the right hand side of equation (5) represents the sum of all energy forms transported to, minus the sum of all energy forms transported from the volume element by mass streams. h_k *is the specific enthalpy of stream k. The integral* $\int_{\dot{Q}_l} \partial \dot{Q}_l$ *represents the total amount of thermal energy/s* $\dot{Q}_l$ *transferred through (part of) the enclosing surface of the volume element of stream l. Transfer to the volume element is positive and transfer from the volume element is negative.* $\sum_m \dot{W}_m$ *is the total amount of work/s done on the volume element minus the total amount of work/s done by the volume element.*

Equation (5) expresses that the accumulation of energy/s in the volume element considered is equal to the total amount of energy/s transferred to this system minus the total amount of work/s transferred from the system. In a steady state process there is no accumulation of energy and that means that the left hand side of equation (5) is zero. In a closed system there are no mass streams to and from the system and that means that the first term on the right hand side of equation (5) (between brackets) is zero. Equation (5) is written for the general case of a non steady state and open process.

1.2.3 Entropy and entropy generation

The second law of thermodynamics introduces the state property called entropy, indicated with the symbol S, which is defined as:

$$dS \equiv \frac{\delta Q_{rev}}{T} \tag{6}$$

In this expression, δQ_{rev} is a small amount of thermal energy transferred in a reversible way, at temperature T. From equation (6) one can deduce that the SI unit of the state property entropy is J/K (Joule/Kelvin). The essence of the second law of thermodynamics is that the state property entropy is not conserved in real processes but, instead, must increase (is generated). This is indicated in equation (7) by the larger than sign:

$$\dot{S}_{generation} \geq 0 \tag{7}$$

Only in the thermodynamic limiting case of reversible processes no entropy generation takes place. This limiting case corresponds to frictionless processes where the driving forces all tend towards zero. It is possible to prove that entropy generation is the sum of the products of the independent driving forces, X, and their related streams, J. This is shown in equation (8):

$$\dot{S}_{generation} = \sum X_i J_i \tag{8}$$

For any process in our material world to proceed in the desired direction, appropriate driving forces must be applied. These driving forces must be as small as reasonably possible to avoid excessive entropy generation.

The second law of thermodynamics can be written in the following balance equation for a volume element:

$$\frac{dS}{dt} = \sum_j \dot{m}_j * s_j + \sum_k \int_{T_b}^{T_e} \frac{\partial \dot{Q}_k}{T} + \dot{S}_{generation} \tag{9}$$

The accumulation of entropy/s in the volume element is equal to the entropy/s transported by mass streams to and from the volume element and entropy/s transfer by thermal energy transferred to and from the volume element through the boundaries of the volume element plus entropy generated. For mass streams, we take entropy entering minus entropy leaving the volume element. For thermal energy we take streams through (part of) the surface to the volume element minus the entropy transported by thermal energy from the volume element.. The last term, entropy generated, is always positive in real processes and zero in the limiting case of reversible processes. In equation (5) there is essentially no generation term and that is the reason why we say that energy is conserved: it can neither be produced nor be destroyed.

1.2.4 Exergy

Based on these two laws of thermodynamics it is possible to define the exergy concept. In thermodynamics one can distinguish three types of systems: closed systems, open steady state systems, and open non steady state systems. This section focuses on an open steady state process, the most often occurring case in the systems investigated: a material stream at a certain place in the process. We ask ourselves the question: how much work can maximally be obtained from the stream considered? Because we know that we cannot obtain any work from thermal energy at the same temperature (T_0) as the surroundings of the process, we can define an appropriate route from the conditions of the stream to complete equilibrium with a reference environment. First we go without transfer of thermal energy to or from our stream to bring our stream to the temperature T_0. At this temperature, we exchange thermal energy with the surroundings such that the pressure of the system becomes equal to the pressure p_0 of the surroundings. All this work is called thermo-mechanical exergy. At T_0 and p_0 we bring the stream to rest and eventually to sea level and convert all remaining forms of work to one form of mechanical work. At these conditions (of T_0 and p_0 at sea level) we often still can obtain work from the system by conversion of the constituents of the stream into the most stable substances or mixtures. This last part is called chemical exergy.

In order to calculate the amount of mechanical energy obtainable from this last step at T_0 and p_0 as easily as possible, it may be that we have to de-mix the constituents of the stream in thought to obtain these constituents in pure form. The amount of mechanical energy related to this process is called the exergy of de-mixing. After conversion to the most stable substances it may be that a mixed state is even more stable. This mixing process leads also to a related mechanical energy effect. The sum of all these contributions to the total amount of mechanical energy obtainable is than called the chemical exergy of the stream.

The total exergy of the stream considered at a certain place and moment in the process is thus the sum of the thermo mechanical and chemical contributions mentioned. The above-mentioned process of reaching thermal, mechanical and finally chemical equilibrium leads to a set of equations from which this exergy value of the stream considered can be calculated. In an analogous way, we can calculate the exergy of a closed system and an open non steady state system at a certain moment and place in the system. As we can see, the temperature and pressure of the environment of our system play an important role and have to be determined with care.

To be able to determine the chemical component of exergy we must say somewhat more about the most stable substances. When only reversible transitions occur at a constant temperature and pressure, we can use the concept of Gibbs energy to determine the most stable situation. In this situation the Gibbs energy has obtained a minimum value. When we do not consider nuclear processes, we have to define the most stable compound of each element or possibly mixtures of some of these compounds for different elements. To be able to determine these compounds, we must have a look at the substances present in our atmosphere, hydrosphere, and lithosphere (about the first 100 m of the crust of the earth). Between them chemical interactions are possible which can lead to the formation of the most stable substances as can be seen from a decrease in the Gibbs energy of the combined system of the atmosphere, the hydrosphere, and the upper part of the crust of the earth. It may be that the speed with which these reactions take place is in reality very small, but in principle we can imagine that these reactions take place very fast until equilibrium is reached. This is obtained when this system has reached its absolute lowest value of Gibbs energy. The chemical exergy values for these substances or mixtures are defined as zero. It is possible to calculate the chemical exergy values for each of these elements from these values. This forms the basis for the calculation of the chemical exergy values for all other compounds.

The calculation of the exergy value of a complex mixture at an arbitrary pressure and temperature is done in the following way. For this calculation we need to know the Gibbs energy of formation of each of its constituents from their constituting elements at standard conditions. In thermodynamics these conditions are the pure constituents at a temperature of 298.15 K and a pressure of 0.101325 MPa.

$$Ex_{chem,j} = \Delta_f G_j^0 + \sum_i |\nu_i| Ex_{chem,i} \quad (10)$$

In equation (10) $Ex_{chem.,j}$ is the chemical exergy of constituent j. $\Delta_f G_j^0$ is the Gibbs energy change of the chemical formation reaction of substance j from its constituting elements in their pure state and at standard conditions. The formation reaction of substance j from its constituting elements is given in equation (11):

$$1 * j = \nu_a * a + .. + \nu_i * i + .. \quad (11)$$

In equation (11):

j is the substance formed from the elements a +..+ i $\neq$ j =...;

ν_a,... ν_l,... are the numbers of atoms/molecules of the elements a, ..., i, which are needed to form 1 molecule of substance j.

From equation (10) it is clear how to determine the chemical exergy of constituent j from its standard Gibbs energy of formation and the standard chemical exergy values of its constituting elements.

Often the simplest procedure to calculate the exergy value of a complex mixture, is to start with the chemical specific or molar exergy values of its constituents. Next take the effects of the difference in pressure and temperature with respect to the standard conditions into account and then multiply these specific/molar values with their mass/molar streams, and finally take into account the effect of mixing these constituents to form the complex mixture. In this way, the total amount of exergy of a complex mixture can be calculated.

The general balance equation for a volume element can be obtained as follows:

By subtracting T_0 multiplied with equation (9) from equation (5) we obtain the equation for the accumulation of exergy in the volume element:

$$\frac{dU + pdV + \sum_j \partial E_j - T_0 dS}{dt} = \sum_k \dot{m}_k (h_k - T_0 s_k) + \sum_j \dot{E}_j + \sum_l \int_{T_b}^{T_e} \partial \dot{Q}_l (1 - \frac{T_0}{T}) + \sum_m \dot{W}_m - T_0 \dot{S}_{generation} \quad (12)$$

In the limiting case of reversible processes, $\dot{S}_{generation} \geq 0$. In this case exergy is conserved. In general $\dot{S}_{generation} > 0$ and this leads to exergy losses. Here we see clearly that in real processes exergy is not conserved but decreases due to exergy losses that are directly related to entropy generation.

1.2.5 Driving forces and their related streams

As an example of a driving force and its related stream, we will consider the transfer of thermal energy through a separating surface from a "hot" medium to a "cold" medium. We will show that in this case $\partial \dot{W}_{lost} = T_0 * \partial \dot{Q} * \left(\frac{1}{T_c} - \frac{1}{T_h} \right)$. The exergy loss/s is equal to the product of a constant, the temperature of the environment T_0, multiplied with a small stream of thermal energy/s $\partial \dot{Q}$ multiplied with the driving force $\frac{1}{T_c} - \frac{1}{T_h}$. This stream of thermal energy/s $\partial \dot{Q}$ occurs as a consequence of the application of the driving force $\frac{1}{T_c} - \frac{1}{T_h}$.

In Figure 1 a $T, \dot{Q}$-diagram is shown for a counter current heat exchanger, where two material streams with different total heat capacities exchange thermal energy. At a certain point in this heat exchanger we suppose that the temperature of the "hot" stream is T_h and of the "cold" stream it is T_c. Here, a small amount of thermal energy $\delta \dot{Q}$ is transferred from the "hot" to the "cold" stream while the temperatures T_h and T_c do not change.

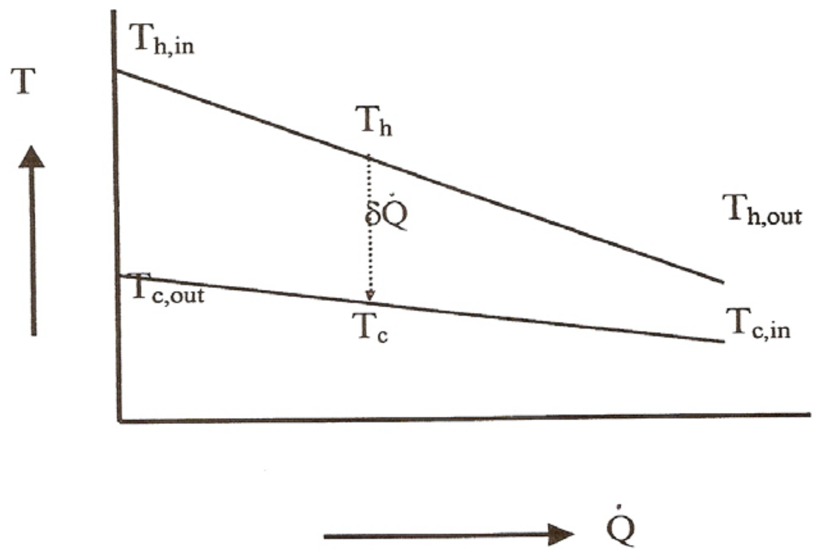

Figure 1: $T, \dot{Q}$-diagram showing a small amount of thermal energy $\delta \dot{Q}$ being transferred from the "hot" stream at T_h to the "cold" stream at T_c.

The maximum amount of power that can be produced from a small stream of thermal energy/s at a temperature T_h, $\partial\dot{Q}$, by means of a Carnot process working between T_h and T_0, is given by Equation (13):

$$\partial\dot{W}_{rev}(T_h) = \partial\dot{Q}\left(1 - \frac{T_0}{T_h}\right) \qquad (13)$$

The expression between brackets on the right hand side of equation (13) is called the Carnot factor. As can be seen from equation (13), the maximum amount of power that can be produced from a stream of thermal energy/s is determined by multiplying this stream with the Carnot factor. When this small stream of thermal energy/s is transferred to the "cold" stream at the temperature T_c then the maximum power that can be obtained from a Carnot process working between T_c and T_0 is given by equation (14):

$$\partial\dot{W}_{rev}(T_c) = \partial\dot{Q}\left(1 - \frac{T_0}{T_c}\right) \qquad (14)$$

When we subtract equation (14) from equation (13) we obtain the power lost by this process of transferring thermal energy/s from a higher to a lower temperature level. This amount of power lost is given in equation (15):

$$\partial\dot{W}_{lost} = T_0\partial\dot{Q}\left(\frac{1}{T_c} - \frac{1}{T_h}\right) \qquad (15)$$

As we can see from equation (15), this transfer of thermal energy/s from a higher to a lower temperature leads to a loss of power. This can be generalized by saying that all possible real processes are characterized by a loss of power. This loss of power in the sub system of the complete heat exchanger, considered so far, can also be related to entropy generation. The total entropy generation in the subsystem considered, is given in equation (16):

$$\dot{S}_{generation} = \partial\dot{Q}\left(\frac{1}{T_c} - \frac{1}{T_h}\right) \qquad (16)$$

By rewriting equation (13), making use of equation (16), we get equation (17):

$$\partial\dot{W}_{lost} = T_0\dot{S}_{generation} \qquad (17)$$

Equation (17) is called the Gouy-Stodola relation. From this relation it can be deduced that a loss of power occurs in the real process considered and that this loss is equal to the product of the temperature of the environment of our (sub) system and the amount of entropy generated in that process.

In equation (16), $\delta\dot{Q}$ is the stream of thermal energy/s transferred from a higher temperature T_h to a lower temperature T_c in the real system considered. In general, such a small stream is indicated by dJ. The term between brackets in equation (16) is called the driving force of the process, and is often indicated with the symbol X. In general, it can be proven that there is a minimum amount of active independent driving forces causing all changes in the system

considered. When the driving force has been defined in a certain unit, the related stream must be expressed in the unit (J/(Ks)/(unit) in which the related force is expressed) e.g. for the transfer of thermal energy by conduction and convection the driving force is $\left(\frac{1}{T_c}-\frac{1}{T_h}\right)=\Delta\left(\frac{1}{T}\right)$ *with 1/K as unit. The related stream must than have the unit (J/(Ks))/(1/K)), this is J/s,(W), and thus the related stream is a stream of thermal energy:* $\dot{Q}$*.*
For the system in general, we can write that the total amount of entropy generation is equal to the sum of the products of the independent driving forces and their related streams. Therefore we can write equation (16) in its most general form as shown in equation (18):

$$\dot{S}_{generation}=\sum_i dJ_i X_i \tag{18}$$

Returning now to equation (15) we can express $\delta\dot{Q}$ *in the following way:*

$$\delta\dot{Q}=UdA(T_h-T_c) \tag{19}$$

In equation (19) U is the overall heat transfer coefficient, dA is the small surface area through which the thermal energy/s is transferred from the medium with the higher temperature to the medium with the lower temperature, and T_h *–* T_c *is normally called the driving force for heat transfer. Note the difference with the driving force for heat transfer related to entropy generation. Substitution of equation (19) in equation (15) results in equation (20):*

$$\partial\dot{W}_{lost}=T_0UdA(T_h-T_c)\left(\frac{1}{T_c}-\frac{1}{T_h}\right) \tag{20}$$

Equation (20) can be rewritten to the form shown in equation (21)

$$\partial\dot{W}_{lost}=T_0UdA\frac{\left(T_h-T_c\right)^2}{T_hT_c} \tag{21}$$

From equation (21) we can see that the loss in power, related to the transfer of thermal energy, is proportional to the temperature difference (T_h – T_c) squared and that this has a larger influence on the loss at lower temperatures. The main goal of the heat exchange process is to transfer a certain amount of thermal energy from one medium to another. This implies that $\delta\dot{Q}$ is a fixed parameter but that the loss of power can be decreased by proportionally increasing d*A* and by decreasing (T_h – T_c). The consequence is that the heat exchange surface area must be increased, which entails extra pressure drops related to the transport of the media. Hence, such increases in heat exchanger surface must be avoided as much as possible. The U value can be reduced by choosing appropriate materials for the heat exchanger and by optimization of the stream conditions to reduce power loss.

From this specific example it will be clear that for all processes we wish to proceed in a specific direction, we must apply appropriate driving forces, but in such a way that the related power losses are minimized. These losses are directly related to extra input of exergy in the process. The most common exergy sources are of fossil origin. Losses can be completely omitted only in the thermodynamical limiting case of reversible processes. In reality, this process can only be approached. We must improve real processes by optimization of the design and their concretization.

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Nomenclature

E	Energy in the form of work [J]
Ex	Exergy [J]
ex	Specific exergy [J/kg]
ex'	Molar exergy [J/mole]
h	Specific enthalpy [J/kg]
J_i	Stream (caused by driving force X_i [unit]) [J/Ks[unit]]
m	Mass [kg]
P	Pressure [Pa]
Q	Thermal energy [J]
S	Entropy [J/K]
s	Specific entropy [J/kgK]
T	Temperature [K]
U	Internal energy [J]
V	Volume [m^3]
W	Work [J]
X_i	Driving force (causing stream J_i) [unit]

Greek symbols

ν_i	Stoichiometric coefficient of element i in the formation reaction of j

Subscripts

i, a	Elements
j	Substance
ch	Chemical
ph	Physical
rev	Reversible process
0	Reference environment state; dead state
c	Lower temperature
h	Higher temperature

Superscripts

.	Per second [1/s]

1.3 A review on exergy analysis of renewable energy-based climatisation systems for the built environment

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1.3.1 Introduction

While the exergy analysis of power plants is a well established research field, this is not necessarily the case for the application of the exergy approach to the built environment. Most of the energy consumption in the building stock is related to near-environmental temperature thermal uses, namely space heating, cooling and hot water production. These low quality energy demands are mainly satisfied with fossil fuels which are high quality or high exergy sources. Therefore, a wide margin for exergy saving exists within the built environment. Since climatisation systems operate closer to the reference environment compared to power plants, a question arises about the suitability of the exergy metrics, mainly developed for plants analysis, for climatisation systems.

Exergy analysis may also be fruitfully applied to renewable energy-based systems in order to identify the optimal and most efficient use of the available renewable sources. Some of these sources may be considered ‘‘purely renewable’’ (e.g. solar energy), while some others are not endlessly available (e.g. biomass), depending on how fast they are consumed in relation with their regeneration time.

In order to determine the state of the art of exergy analysis of building energy systems based on renewable energy sources a review of the literature is mandatory and helpful. Results from the different analyses can be brought together and common conclusions regarding this thermodynamic assessment of building energy systems can be drawn. Strengths, weaknesses and required future research can be identified. In this paper the main issues regarding the methodological aspects are discussed in item 1.3.2. Items 1.3.3 and 1.3.4 are dedicated to the comparison of the results of applying the exergy analysis to heating and cooling systems. Finally, general conclusions are reported in item 1.3.5. A more extensive review can be found in Torio, Angelotti and Schmidt (2009).

1.3.2 Methodologies

Reference environment

The chosen reference environment strongly affects the results of exergy analysis. Rosen and Dincer (2004) evaluated the sensitivity of exergy flows as a function of different definitions of the reference environment. In equation (1) the quotient of the difference in thermal exergy flow at T with respect to T_0 and at T with respect to $T_0 + \Delta T_0$ and the exergy value of the thermal energy flow at T with respect to T_0 is shown. This quotient is also called the relative sensitivity σ of the thermal exergy value due to a change in T_0 equal to ΔT_0.

$$\sigma = \frac{\Delta T_0}{T - T_0} \tag{1}$$

As it is analytically shown, the sensitivity of exergy assessment is greater when the properties of the system are close to those of the reference environment. This justifies that usually constant reference environments are assumed for the exergy analysis of power plants and industrial processes involving high quality energy forms as main output. In turn, in the built environment, energy demand happens at conditions close to those of the reference environment. Subsequently, they undergo strong variations for changing environment and/or system conditions. This justifies the necessity to apply and establish a method for dynamic exergy analysis for the building sector, where the reference temperature is time dependent. However, in the literature, mainly static exergy analysis of building systems can be found (Schmidt, 2004; Cervantes, Torres-Reyes, 2002; Pons et al. 1999; Izquierdo et al., 2002; Dincer and Rosen, 2007; Marletta, Evola, Sciurella, 2007; Hepbasli, Akdemir, 2004; Dikici, Akbulut, 2008; Saitoh et al., 2003; Ozgener, Hepbasli, 2007; Xiaowu, Ben, 2005; Chaturvedi, Chen, Kheireddine, 1998; Koroneos, Spachos, Mossiopoulos, 2005; Torres-Reyes, Picon-Nuñez, Cervantes-de-Gortari,, 1998). Dynamic exergy analysis are still the exception (Alpuche et al.2005; Angelotti, Caputo, 2007; Torio, Schmidt, 2008; Nishikawa, Shukuya, 1999; Sakulpipatsin et al., 2006; Sakulpipatsin, 2008).

Considering steady state approaches, the reference temperature can be chosen using several criteria. For example: seasonal mean values, annual mean values and design conditions. Following the considerations on the sensitivity of exergy flows, each of these choices would significantly influence the results of an exergy analysis. In addition, they would complicate comparing among results from different analyses. Since, to the best of the authors' knowledge, there is no common agreement for a proper definition of the reference environment for steady state analysis, future work in this direction is required.

The discrepancy between the results of steady state and dynamic state exergy analyses of space climatisation applications have been investigated by different authors. In typical winter evaluations, if mean monthly or seasonal outdoor temperatures are used as the constant reference temperature throughout the calculations, mismatching with dynamic results is found to be around 3-10% (Sakulpipatsin, 2008; Angelotti, Caputo, 2007). However, under summer climatic conditions indoor air temperature is much closer to the outdoor temperature. Thus, Carnot factors, and subsequently the exergy flows associated to space cooling, undergo dramatic variations for changing outdoor air conditions. As a consequence, steady-state estimations of the exergy flows for cooling applications lead to errors which can be as high as 75% of the assessed exergy flow (Angelotti, Caputo, 2007). Furthermore, using mean outdoor temperatures for the cooling period might result in outdoor temperatures below the indoor set point of 26°C, subsequently making the estimation of any cooling load impossible.

Although further investigations would be recommended, it can be inferred that steady-state exergy analysis might be reasonable for a first estimation of the exergy flows in space heating applications, particularly in colder climates. The error is expected to be bigger the milder the climatic conditions are. However, exergy flows in cooling applications can only be assessed by means of dynamic analysis, where variations in outdoor reference conditions are taken into account.

So far the reference environment has been regarded as the reference temperature T_0. However, in climatisation applications the humidity content of the outdoor and indoor air may also play a role. Sakulpipatsin (2008) evaluated the influence of including the air humidity in the definition of both the building system and its reference environment on the exergy flows through the building envelope. Two different climatic conditions were investigated: Bangkok (Thailand, hot and humid) and De Bilt (The Netherlands, cold and dry). In both cases, taking into account the dynamic variations in the indoor and outdoor air humidity lead to the most accurate estimation of the exergy flows. In turn, omitting ambient air humidity (i.e. regarded as zero or equal to indoor air humidity), leads to underestimations in the exergy flows. Differences of up to 86% in the total annual exergy flows for the hot and humid climate and around 3% in the cold dry climatic conditions arise.

In hot and humid climatic conditions, buildings are usually equipped with cooling systems managing the temperature and indoor air humidity. As a result, in- and outdoor air humidity might differ significantly from each other. In this case, it is of great importance to include the humidity in the definition of the system and its environment. In turn, in cold drier climates where the differences between indoor and outdoor air humidity is significantly lower, humidity can be omitted from the definition of both the system and its environment without significant losses in the accuracy of the exergy flows.

Exergy performance indicators

Exergy efficiencies are a suitable and appropriate base for comparing the performance and optimisation of different heating and cooling systems. As any other efficiency, exergy efficiencies are defined as the ratio between the obtained output and the input required to produce it. Exergy efficiencies help identify the magnitude and place of exergy destruction (Cornelissen, 1997) within an energy system, and thus, those systems whose operation is closer to ideal or where the energy and exergy inputs of the system are better used. However, several different definitions of exergy efficiency parameters can be found in the literature. At least two types of exergy efficiencies can be identified and differentiated: “simple” or “universal” and “rational” or “functional” (Cornelissen, 1997; Tsatsaronis, 1993). Their mathematical expressions are shown in equations (2) and (3):

$$\psi_{simple} = \frac{Ex_{out}}{Ex_{in}} \quad (2)$$

$$\psi_{rat} = \frac{Ex_{des,out}}{Ex_{in}} \quad (3)$$

The simple exergy efficiency is an unambiguous definition for the exergy performance of a system. However, it works better when all the components of the incoming exergy flow are transformed into some kind of useful output (Cornelissen, 1997). In most of the building systems this is not the case, since some part of the exergy input is fed back and does not constitute a useful output strictly speaking. For example. in a hydronic heat or cold emission system in a building, outlet water flows back via return pipes into the heat/cold generation system. The simple efficiency gives a figure on how close are the processes involved to the ideal performance.

The rational exergy efficiency accounts for this difference between “desired output” and any other kind of outflow from the system. Therefore, it is a much more accurate definition of the performance of a system. It is a term that can be better used without taking to misleading conclusions. The rational efficiency shows how much potential is getting lost in providing a specific output. Exergy losses regarded in the rational efficiency are due to both irreversible (not ideal) processes and unused output exergy flows.

Starting from the idea that many existing exergy efficiency definitions were developed for use with larger temperature differences and further from the environmental temperatures, Boelman and Sakulpipatsin (2004) presented a critical analysis of exergy efficiency definitions to be potentially used in the field of exergy analysis of building services. Taking into account a simple heat exchanger operating at near-environmental temperatures, they study the sensitivity of both the simple and the rational exergy efficiency to outdoor temperature, fluid inlet temperatures and thermal effectiveness of the heat exchanger. They find that the rational exergy efficiency is more sensitive to the above mentioned parameters.

The exergy performance of a building climatisation system is evaluated in terms of its rational exergy efficiency in the Geneva canton building regulation (Favrat, Marechal and Opelly 2007). Adopting a modular approach, the building system and its supply chain are subdivided into four subsystems (room convector, building plant, district heating or cooling plant and power plant). For each subsystem, a “single” exergy efficiency is firstly calculated and then an “overall” exergy efficiency is derived. Exergy efficiency is further addressed in chapters 2 and 4, and in section 1.5 of this book.

While exergy efficiency is a very general performance indicator, the so-called “exergy expenditure figure” developed by Schmidt, Torío and Sager (2007) has been especially introduced for characterising the exergy supply in buildings. In equation (4) the exergy expenditure figure is defined for a general component *i* of an energy system. This parameter is calculated as the ratio of the exergy input required to supply a given energy demand (effort) and the provided energy demand (use). Therefore, it represents a kind of quality factor (exergy to energy ratio) of the energy processes occurring in the given component. Energy and exergy losses in the component are implicitly taken into account by the ratio of provided output to required input. In consequence, if the energy losses in the component are high, i.e. low energy efficiency, the exergy expenditure figure might reach values higher than 1.

$$\varepsilon_i = \frac{Effort}{Use} = \frac{Ex_{in,i}}{En_{out,i}} \tag{4}$$

This parameter needs to be compared to the exergy to energy ratio of the energy demand to be provided, i.e. to the quality factor of the energy demand. Values close to the exergy to energy ratio of the energy demand indicate a good match between quality levels (i.e. exergy) of the energy supplied and demanded. In turn, values diverging from the exergy to energy ratio of the demand indicate bad matching and, in consequence, lead to conclude that other energy sources shall be used for providing that specific use and/or that energy losses need to be reduced. The exergy expenditure figure is discussed in section 2.3 of this book.

For the particular application of space heating and cooling of buildings, the quality factors (or exergy to energy ratio) of the energy demand are very low. In Figure 1 it is shown graphically that for space heating applications, at reference and indoor air temperatures of 0°C and 21°C respectively, this quality factor of energy demand is found to be 7%. Therefore, for space heating of buildings, the closer the exergy expenditure figure for a given system to 7%, the better the system exergy performance is. Subsequently, in space heating and cooling applications, lower exergy expenditure figures indicate more optimised energy supply systems.

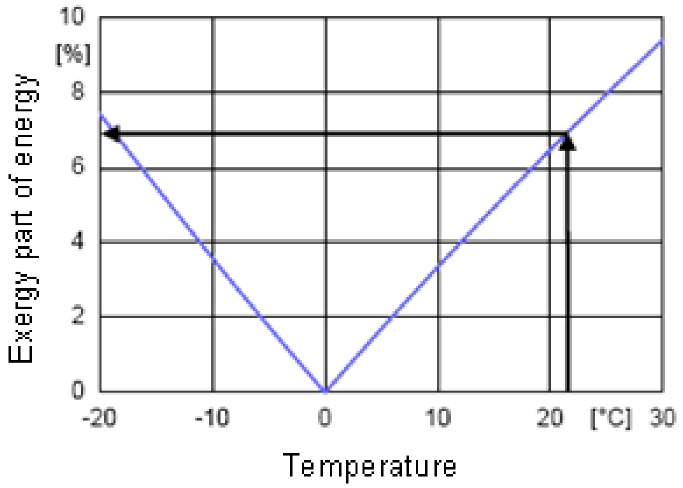

Figure 1: For a reference temperature of 0°C, the exergy content of the energy in the room air, assuming an indoor air temperature of 21°C, is 7%.

1.3.3 Applications to renewable energy-based heating systems

Solar thermal systems

Solar thermal systems provide heat at different temperature levels depending on outdoor conditions and implemented control strategies. Out- and inlet collector temperatures strongly determine the energy efficiency of the solar thermal system. The strong influence of these parameters is reflected both in energy and exergy terms.

For exergy analysis of solar thermal systems, two different frameworks can be found in the literature: (1) the conversion from solar radiation into low temperature heat is included in the analysis and solar radiation is the first exergy input in the system (Bejan, 1982; Gunherhan, Hepbasli, 2007); (2) heat output from the solar collector field is evaluated as given output from the system and the conversion from solar radiation into low temperature heat is disregarded in exergy terms (Torío, Schmidt, 2008; Meir, 2002; Sandnes, 2003).

Several authors using the first analysis framework (1) conclude that outlet collector temperature should be maximized (for the given outdoor conditions) so as to increase exergy efficiency of the collector field (Bejan, 1982; Gunherhan, Hepbasli, 2007). Using this framework for the analysis of a given solar thermal system, the overall efficiency would mainly depend on the incident solar radiation (collector area) and energy demand to be supplied (building). For a given building, energy and exergy demand for space heating applications would also be fixed. Thus, control strategies and different outlet temperatures would not have any influence on the overall exergy efficiency of the solar collector field as part of a building space heating system, and an optimization based on this parameter would be peddling.

The second analysis framework (2) allows distinguishing the influence of different control strategies of the solar system. Particularly if a whole system analysis is carried out, i.e. including the final exergy demand for domestic hot water (DHW) or space heating as final output of the system, increasing collector outlet temperatures beyond the required temperature level of the energy demand might reduce exergy losses in the collector field, but would increase energy and exergy losses in the storage tank, distribution and emission systems. Following, greater mismatching between the solar energy supplied and the actual exergy demanded would arise, and the overall exergy efficiency of the whole system would be expected to decrease. An example of dynamic exergy analysis of solar thermal systems using both approaches can be found in Torío and Schmidt (2008).

Ground coupled heat pumps

The boundary and framework chosen for exergy analysis of heat pumps also plays a major role in the results obtained, as also illustrated in section 4.1 of this book. Again, a unitary framework for exergy analysis of these systems could not be found (Torío, Angelotti and Schmidt 2009). Hepbasli and Akdemir (2004) and Akpinar and Hepbasli (2007) regard only electricity as energy/exergy input into the heat pump. They disregard the exergy of energy flow from the ground. In turn, Ozgener and Hepbasli (2007), Esen et al. (2007) and Hepbasli and Tolga-Balta (2007) include the exergy flow from the ground as input for the heat pump to assess its exergy efficiency.

Ozgener and Hepbasli (2007), Esen et al. (2007) and Hepbasli and Tolga-Balta (2007) regard the exergy demand of the emission system at its temperature level as final demand. Hepbasli and Akdemir (2004) regard the final demand as the energy required by the room or building. The chosen reference temperature also varies significantly per author: in Hepbasli and Akdemir (2004) it is 25°C, while Ozgener and Hepbasli (2007) take the design heating temperature of the site, and Hepbasli and Tolga-Balta (2007) consider the average outdoor temperature of the site during the calculation period. The influence of ground temperature on ground coupled heat pumps is also addressed in section 4.1 of this book.

As a consequence overall exergy efficiencies for several heat pump units vary greatly: from almost 3% to 80% (this variation is remarkably greater than that of the energy performance figures regarded: the coefficient of performance (COP) is between 1.65-2.80). Also dependent on the boundary is the component identified to have greatest improvement potential within the heat pump cycle (i.e. compressor, condenser, evaporator and expansion valve). Since the exergy efficiency of a heat pump strongly decreases as the reference temperature increases, steady-state reference conditions chosen in each study are expected to strongly influence the results from an exergy analysis. This disables the comparability of the obtained results. This highlights once again the importance of establishing a common framework and unitary method for exergy analysis of building systems.

Solar assisted heat pumps

Cervantes and Torres-Reyes (2002) successfully use exergy analysis to derive optimisation possibilities of a solar assisted water-to-air heat pump system. The authors suggest control strategies which would increase the performance of the system. They found an optimum value of the evaporation temperature as a function of the environmental conditions (radiation and air temperature) and collector properties. Control strategies aimed at this optimum evaporation temperature yield the highest exergy efficiency for the system.

Several heat pump systems with different environmental heat sources (air, solar, ground) are investigated by Dikici and Akbulut (2008). The better performing system varies, depending on whether energy or exergy is chosen as evaluation criteria. However, the authors do not clarify how to achieve a compromise or suitable choice based on both parameters, if their behaviour is contradictory. This highlights the necessity of a common evaluation framework for exergy analysis, which should also clarify the role of exergy assessment on the energy systems planning and design.

Biomass boilers

According to the German regulation (DIN 18599:2007), wood pellets and bricks (i.e. biomass based fuels) for warm water and space heating applications are regarded as a mainly renewable energy source. However, wood is not endlessly available as renewable source to cover energy demand, since cutting down the total forested area of a country would be neither renewable nor sustainable, and the CO_2-emissions cycle could not be regarded as closed any more. Thus, an efficient use of wood as energy source should be pursued.

Wood is a highly valuable energy source (i.e. with high exergy content). Exergy analysis regards the quality of energy sources, but not its renewability or CO_2 neutrality. Thus, its use to supply low temperature (i.e. low exergy) applications comes along with high exergy losses, representing a non-optimized solution. The overall exergy performance of a wood-pellets boiler, for instance, is similar to that of a condensing boiler: 5.53% and 5.9% respectively. For wood-boilers, results from energy and exergy analysis are contradictory to one another: from a fossil primary energy perspective wood would always be advisable (due to its CO_2 neutrality); in turn, its exergy efficiency is just as low as that of a conventional boiler, and lower than that of low-exergy systems such as solar thermal units or ground-source heat pumps (7.4%). In this case, exergy analysis would help in pinpointing space heating by direct burning of wood as an inefficient energy supply system. It leads to conclude that wood, as high quality energy source, should rather be used for high quality uses, such as electricity production or combined heat and power production (CHP units).

1.3.4 Applications to renewable energy-based cooling systems

Thermally driven compression cycles

Several authors have used exergy analysis to improve the performance and operation of thermally driven compression machines for cooling applications (Pons et al., 1999; Boer et al., 2007; Khaliq, Kumar, 2007; Morosuk, Tsatsaronis, 2008; Sencan et al., 2005). The main conclusion is that the generator and absorber are components of the cooling cycle where more irreversible processes occur and, thus, where optimization efforts should be focused in first place. However, holistic and detailed analysis performed on the whole cycle (i.e. including all components and their interrelationship) (Boer et al., 2007; Morosuk, Tsatsaronis, 2008) shows the strong interdependence between the irreversibilities of the different components. Thus, if the performance of the whole cycle is targeted, overall exergy consumption instead of irreversibilities in only one specific component (even being that with greater exergy consumption) should be minimised. Furthermore, reducing the generation temperature leads to higher exergy efficiency of the system, despite lowering their energy performance (Sencan et al., 2005; Pons, 1999).

Studies found by the authors focus in the analysis of the absorption cycles as a component of the energy supply chain of a building demand. However, analysis of the whole energy chain is required in order to ensure that proposed control strategies lead to a more optimised use of the energy flows in building cooling applications.

Desiccant cooling systems

Results of an exergy analysis of desiccant cooling units leads to conclude that regeneration and re-heating temperatures should be lowered. A similar trend can be derived from a primary energy analysis of the systems. In terms of primary energy and exergy efficiency, results are also coherent and lead to similar conclusions (Marletta, 2008).

Solar coupled desiccant cooling systems are always advisable from an energy and exergy perspective against conventional compression cooling machines. Their performance increases significantly with higher solar fraction: exergy efficiency increases from about 3% (without solar system) to around 8% (with 100% solar fraction).

1.3.5 Conclusions

From the above statements the following general conclusions about exergy analysis of building systems based on renewable energy sources can be derived:

- a common framework for exergy analysis of several building systems is lacking. Efforts should be conducted to create a unitary framework for exergy analysis. Furthermore, boundaries and the regarded energy processes should be always clearly stated since they dramatically influence results and conclusions of exergy analysis;

- a methodology on how to combine and apply conclusions from energy and exergy analysis to building systems, when contradictory assessment is provided by both analyses, should be devised. This would help clarify the benefits and scope of exergy analysis to the wider public and also constitute the mandatory condition for any proposal dealing with the application of exergy indicators in a normative framework;

- renewable sources are not necessarily low exergy sources. A pending question is whether it is more important to save primary energy (that means using less fossil fuels and renewable resources) or to save primary exergy (that means using renewable and non-renewable energy sources in the most efficient way). Further debate on which should be the final objective of a combined energy and exergy analysis of climatisation systems would be necessary.

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1.4 Zero energy building – definitions

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1.4.1 Introduction

Buildings have a significant impact on energy use and on the environment. In Europe, buildings for households and services account for 40% of the total energy consumption: this is more than industry or transport (European Commission, 2012). Keeping our homes comfortable requires large amounts of energy. Almost half of the average home's energy consumption is used for heating. Another 17% is used for water heating, 6% for cooling and 5% for refrigeration. In Europe, almost a quarter of the energy used in homes is used for lighting and appliances.

There are different types of energy sources. 40% of the energy is extracted from petroleum. The supply is not endless. Experts predict that the Peak Oil is around 2030. Natural gas is the second most used energy source. The world gets almost a quarter of its energy from natural gas. The consumption of natural gas has nearly doubled in the last 30 years. The third most used and also the last fossil fuel is coal. Coal has the most widely distributed reserves: it is mined in over 100 countries, and on all continents except Antarctica. The largest reserves are found in the USA, Russia, Australia, China, India and South Africa. Not all the mines are discovered yet, so it is not exactly known when the reserves will be used.

Second to fossil fuels, uranium is the most used energy source. The world's top producers are Canada (28% of world production) and Australia (23%). Other major producers include Kazakhstan, Russia, Namibia and Niger. With 3.3 million tons of uranium ore, all 436 worldwide operating nuclear power plants can be supplied for several decades.

In conclusion**:** many of the resources are running out. Therefore, world’s energy needs must be more covered by renewable energy sources. They are now only responsible for 7 % of total energy use.

1.4.2 The advantages and disadvantages of ZEB

A zero energy building (ZEB) produces at least as much energy as it consumes on an annual basis, with zero carbon emissions. This design principle is gaining interest as renewable energy is an important way to cut greenhouse gas emissions. It is also one promising path towards LowEx communities, as a ZEB is capable of significantly reducing a building's exergy demand.

There are numerous advantages when constructing a zero energy building. The most cited advantage is the reduced total cost of ownership due to improved energy efficiency. In addition, the improved insulation increases the indoor comfort due to more-uniform interior temperatures and safeguards the owner from future energy price increases. Generally, a higher resale value is also a consequence.

As a disadvantage may be regarded the initial costs, which can be higher. Other disadvantages are that few designers or builders have the necessary skills to build ZEBs and climate-specific design may limit future ability to respond to global warming.

The most cost-effective energy reduction in a building usually occurs during the design process. Sunlight and solar heat, prevailing breezes and the cold of the earth below a building, can provide day lighting and stable indoor temperatures with minimum mechanical means. ZEBs are optimized to gain passive solar heat and use shading to limit overheating. Combined with the thermal mass of the building, that stabilizes temperature variations throughout the day.

There are several steps to achieve a ZEB. First choose the right orientation for the building to have sunlight on the right places, then reduce energy consumption by right design of the building, and subsequently include renewable energy by using wind and solar power.

1.4.3 Different definitions of zero energy building

The definition used for a zero-energy building usually varies per country. In general, a zero energy home is designed to produce as much energy as it consumes over the course of a full year using assumptions for typical occupant behaviour. This can be measured in different ways: relating to cost, energy or carbon emissions and so resulting in multiple definitions for the same concept. Some of the most typical definitions are presented below.

In most of the on-the-grid buildings, the homes exchange energy with the power grid. They deliver energy to the grid when the building's own energy generation system (e.g. photovoltaic) produces more energy than is being used and draw from the grid otherwise. Same applies to heat, but this option is less used today. In future, when heat trading becomes more accepted and supported by the heat networks and operating systems, it will contribute to the energy balance of the on-the-grid ZEBs.

An off-the-grid ZEB has no connection to utility nets, and because of that, it has to store energy for later use. This makes off-the-grid ZEBs harder to realize. We need to be aware that most definitions do not include the emissions generated in the construction or the embodied energy in the structure. In a ZEB, the amount of energy used to fabricate the building materials could outweigh the energy saved over its useful life span.

Off the grid: stand alone ZEB

Off the grid homes are autonomous. They do not rely on municipal water supply, sewage, natural gas, electrical power grid or similar utility services. Electrical power can be generated on-site from renewable energy sources. These sources capture their energy from existing flows of energy, i.e. solar power, wind power, wave power, hydropower, bio-fuel (such as produced by anaerobic digestion) and geothermal power. The energy supply also has to cover for storage and other losses. On-site water sources can include a well, stream or lake. Depending on the water source this may include pumps or filtration.

Advantages: increased security, less CO_2-emissions, independency of the energy market prices and reduction of environmental impacts by using on-site resources (sunlight, rain).

Disadvantages: growing all of your own food is more time-consuming; autonomous living can require sacrificing lifestyle choices and personal behaviour, some find it isolating.

There are several systems used to cover the water need in off-the-grid buildings: grey water systems (using wastewater to water plants and flush toilets), composting toilets and a solar still osmosis (to distil water). To generate electricity, solar cells and wind turbines are used. For heating and cooling, passive solar design is used e.g. a Trombe wall (sun-facing wall that uses thermal mass), earth sheltering, concrete core activation and heat recovery ventilation. Finally, to have warm water, a solar boiler, cogeneration and hot water recycling is required. (Off the grid 2009)

On the grid: Net zero on-site energy use (also called “site ZEB”)

In this type of ZEB (mostly used in the USA), the amount of energy provided by on-site renewable energy sources is equal to the amount of energy used by the building (Torcellini et al. 2006).

Generation includes PV cells or solar hot water collectors. A limitation of a site ZEB definition is that the values of various fuels at the source are not considered. For example, one energy unit of electricity used at the site is equivalent to one energy unit of natural gas at the site, but electricity is more than three times as valuable at the source (no losses of transportation). For all-electric buildings, this “site ZEB” is equivalent to a “source ZEB” defined below. For buildings with significant gas use however, a site ZEB will need to generate much more on-site electricity than a source ZEB. It can be easily verified through on-site measurements (Torcellini et al. 2006).

Net zero source energy use (also called “source ZEB”)

The “zero primary energy building” or “zero energy source building” or “source ZEB” in short recognizes that the off-site supply of energy, particularly electricity production, is very inefficient. Typically only around 35 % of the energy used in a traditional fossil fuel power plant is converted to electricity, with the remainder lost if no waste heat recovery or combined cycles are used. Further losses accumulate during electricity transmission. Because of this, in order to meet the definition of zero primary energy use, the amount of electricity exported must be substantially higher than the amount of energy registered on the electricity meter. To calculate a building’s total source energy, both imported and exported energy are multiplied by the appropriate site-to-source energy factors. To make this calculation, power generation and transmission factors are needed.

Net zero energy cost

Net zero energy cost relates to the price of energy. In such a building, the cost of purchasing energy is balanced by income from on-site generated electricity sold to the grid. Whether this balance can be preserved over the medium to long term is subject to changes in energy prices. The money received for the exported electricity will have to compensate energy, distribution, peak demand, taxes, and metering charges for electricity and gas use. In wide-scale implementation scenarios, this definition may be ineffective because service rates will change dramatically. For commercial buildings, a cost ZEB is typically the hardest to reach, and is very dependent on how net electricity generation and its structure is credited.

Net zero energy emissions

Outside Canada and the US, a net zero energy building is usually defined as one with zero net energy emissions, also known as a “zero carbon building” or “zero emissions building”. Under this definition the carbon emissions generated from on-site or off-site fossil fuel use, are balanced by the amount of on-site renewable energy production. This includes not only the carbon emissions generated by the building in use, but also those generated in the construction of the building and the embodied energy of the structure. The net zero emissions ZEB definition has some calculation difficulties. Many of these difficulties are related to the uncertainty in determining the source of electricity generation.

1.4.4 Decision to build or not to build – and how big

One of the answers to reducing raw material- and energy-consumption is to evaluate whether a new building really needs to be built. Renovating an existing building can save money, time, and resources. It also enables a family or company to be located in a part of town with existing infrastructure and public transportation, enhancing convenience and reducing sprawl. Next, if a new building is required, it should be sized only as large as it really needs to be - contrary to the cultural assumption that we should buy or lease as much square meters as we can afford. Smaller buildings require fewer building materials, less land, and less operational energy. Furthermore, smaller houses and commercial buildings allow the budget to be spent on quality, rather than, what may be underused, quantity.

1.4.5 Design

The most cost-effective energy reduction in a building usually occurs during the design process. Great opportunities lie in simple design solutions that intelligently respond to location and climate. It is during the design stage that the highly cost-effective strategies to realise a substantial energy demand reduction are selected.

Three steps need to be followed to achieve a ZEB: first reduce the energy demand to 15 kWh/m² (with airtight building, adequate insulation, heat recovery by heat pumps and well chosen ventilation systems, at least double layered glass) and use energy-efficient equipments inside. Then use an efficient system for heating and hot water, and good blinds to prevent overheating. Finally, obtain the remaining energy from renewable energy sources (EIA 2009).

Reduce heating and cooling loads

Making the building envelope (exterior walls, roof and windows) as efficient as possible, taking in consideration the climate, can dramatically reduce heat loads. For residential buildings and other small buildings, optimal sealing, insulation, and radiant barriers, can reduce heat losses to less than half that of a building that simply meets the requirements of the building code. Once the building envelope is efficiently designed to reduce heat flow, natural heating and cooling methods can be used to greatly downsize, or even eliminate, fossil fuel-based mechanical heating and cooling systems. Techniques used for reducing the heat load include solar heating, efficient and right-sized HVAC systems with heat-recovery units and utilization of waste heat.

The cooling load (the excessive heat) is generated inside the building by lights, equipment, and people. Installing efficient lighting and appliances (which emit less heat), will significantly reduce the building's cooling load. Furthermore, using daylight as much as possible will reduce cooling loads even more, because daylight contains the least amount of heat per lumen of light when adequate solar protection is used. Other techniques include natural ventilation and cooling, and also the efficient and right-sized HVAC systems.

These previous points can be integrated into a passive solar design which uses the sun's energy, together with appropriate building features, for the heating and cooling of living spaces to maintain interior thermal comfort. It does not require mechanical systems, and therefore only minimal maintenance is needed. This passive design mostly uses thermal mass, which stores heat. The thermal mass is used for cooling or heating, depending on the climate. Other commonly found elements in this type of design are operable windows and thermal chimneys (used for natural stack ventilation).

Use efficient equipment

Beyond the design stage, there are a number of efficiency measures that can be utilized. Efficiency measures provide the same or better benefit at no inconvenience to the user. For example: selecting a more energy-efficient air conditioning system that produces the same amount and quality of cooling, while using less energy.

It should be kept in mind, that over a building's lifetime, the equipment, windows and light fixtures may be improved thus enabling the building to perform at a higher level. But even with similar improved components, a building that merely meets the requirements of the building code might not perform at the level of the building with the better design.

Supply the remaining energy with renewable energy sources

There are numerous technical and technological possibilities to exploit renewable energy sources. Many naturally occurring phenomena contribute to supplying renewable energy without damaging the environment, which helps to avoid pollution in urban areas and in locations on large and small scale.

Solar cells are becoming more efficient, transportable and flexible, thus allowing easier installation. PV can power applications of all sizes. Wind farms installed on agricultural land or grazing areas have one of the lowest environmental impacts of all energy conversion technologies. Wind turbines are also available as a single-family house application. Ground source heat pumps are one way to harness the solar energy stored in shallow soil. Biomass is a renewable source regarded as CO_2 neutral since new growth (of biomass) binds the CO_2 emitted from the combustion or anaerobic digestion of the harvested biomass.

1.4.6 Sustainable building in different countries

Searching for adequate standards to measure energy use in ZEB buildings, as the part of the Sustainable Buildings Group, is a long ongoing process. There are various rating systems for Sustainable Buildings worldwide. Many countries have developed their own standards of energy efficiency for buildings such as Energy Performance of Buildings - EPB (Belgium), Leadership in Energy and environmental Design standard for Green Building design - LEED (Brazil, Canada, India, Mexico, USA), Green Star (New Zealand, Australia, South Africa), BRE Environmental Assessment Method - BREEAM (The Netherlands and the UK).

Nowadays, the problem of increasing energy use in buildings finds its place in official international codes. The Investment Property Databank Environmental Code is a new initiative in this field. The IPD Environment Code was launched in February 2008: it sets a new global standard for measuring the environmental performance of buildings which are responsible for 20 % of global CO_2 emissions. The code covers a wide range of building types from offices to airports (IPD 2009).

LEED and BREEAM are the two most popular systems for ecological certification of buildings. European Investors choose the BREEAM system, American Investors use LEED. Both systems give analyses in similar categories: energy, water, land parcel, interior air quality, materials and waste.

1.4.7 Monitoring

Knowing how buildings use energy is key to optimizing resource allocation and improving energy efficiency. Residential buildings have big carbon or energy footprints (residential and commercial buildings account for ca. 40 % of the E.U. final energy demand). If the origin of the footprint is found, something can be done about it. That is why monitoring energy use and energy savings is essential. The formula for success is: energy efficiency + renewable energy + monitoring and visualization = sustainable high performance buildings.

There are different monitors available. Examples are the carbon footprint monitor (that can be used for the whole lifestyle or just for the home) and sun flow monitor. There are even user-friendly systems available, such as the energy flow program for iPod. This enables easy monitoring of a house's energy flow. Of course, every renewable energy conversion system must be checked and improved frequently so the yield remains stable throughout the system lifetime.

Temperature measurements for building energy evaluation purposes are less difficult than many other measurements for engineering applications, because accuracy requirements are typically not as tight, environmental conditions are less extreme and response times can be longer.

1.4.8 Materials

Naturally, the extraction, manufacturing, use and disposal of building materials have an impact on the environment. In each of these phases significant quantities of raw materials, water and energy are used. The embodied energy for building materials is estimated to account for more than 10 % of a conventional building's total energy use over a 50- 100 year life cycle.

Embodied energy is not occupant dependent – the energy is 'built into' the materials. Embodied energy content is incurred once (apart from maintenance and renovation) whereas operational energy accumulates over time and can be influenced throughout the life of a building. Thus, as buildings become more energy efficient, the impact materials have on the total life cycle energy consumption of a building will become more significant. The resources used to produce or recycle a material could minimize the energy savings over its useful life span. The embodied energy and the ecological footprint of materials are therefore characteristics that need to be taken in consideration while designing or renovating a building. The usage of green- or sustainable materials is an effective way to achieve low embodied energy and small ecological footprint.

A "perfect" green or sustainable building material would have no negative environmental impacts and might even have positive impacts like land, water or air purification. Such a material would be infinitely reusable or recyclable and its production would be supported indefinitely by nature. Finding materials which answer to this stated description is not simple but some do exist. An example is lumber from forests certified to be sustainably managed.

In practice there are materials that significantly reduce the negative impacts on people and the environment. Rapidly renewable plant material is typically considered a green material. But also other products that are renewable, reusable or recyclable can get the 'green' status. Given that several factors play a part, selecting materials is not an easy task. For example, one should consider the climate where the building is going to be constructed because this determines the characteristics the materials need to have. However, one also needs to examine the sources of the raw materials and the amount of recycled content and later recyclability of materials, as well as the total life cycle cost (including the costs of production and maintenance), the embodied energy and the transport.

However, despite the complexity, some rough guidelines can be stated: use durable materials; use low-maintenance materials; minimize packaging waste; use low embodied energy building materials preferably made from sustainable resources; preferably use locally produced building materials; use recycled building products.

1.4.9 Conclusions

To realize a new Zero Energy Building, the goal is to achieve at least two-thirds energy reduction with (passive solar) design and efficiency. The remaining one-third should be supplied from renewable energy sources. Different types of installations can be used to generate the required heat and power on- or off-site. When renovating, one should find a balance between costs and energy reduction. When the costs of reaching zero energy standard are too high, one can opt to realize a Near Zero Energy Building (stricter than a passive house) or a passive building.

The embodied energy of materials, either when renovating or building new, is a factor that should not be forgotten. When taking the time to weigh the advantages against the disadvantages of different materials, one can select materials with a minimized environmental impact while still featuring the desired characteristics.

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1.5 Definition of LowEx Systems for the built environment

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1.5.1 Introduction

This section presents and discusses exergy-related definitions and approaches relevant to the built environment. It attempts to relate paradigms from different professions, traditionally focused on demand (e.g. building science), supply (e.g. mechanical engineering) or resources (e.g. industrial ecology, chemical engineering).

Exergy is a useful thermodynamic-based concept for assigning a quantitative quality mark to a stream or a product. Exergy allows describing and quantifying the potential of energy to do useful work and/or to be dispersed, as further discussed in sections 1.1 and 1.2 of this book.

The application of exergy to buildings and building services is relatively recent (Shukuya and Komuro, 1996; Shukuya, 2004). Exergy is, however, a well established engineering tool in the study and improvement of complex thermodynamic systems in energy engineering and chemistry. Some authors (e.g. Fraser and Kay 2002) argue that exergy analysis also has the potential to provide important insights into ecosystem organization and function.

In this section, item 1.5.2 presents and discusses working definitions related to exergy, efficiency and reference environment. Item 1.5.3 briefly addresses some of the key assumptions underlying the efficiency and consumption paradigms, as well as exergy-related aspects of thermal interaction between buildings and their immediate surroundings. Item 1.5.4 concludes the section.

1.5.2 Definitions

Exergy, also known as available energy, is a thermodynamic quantity that provides a measure of energy quality. It is based on the first and second laws of thermodynamics, and considers both the quantity and the quality of energy.

Unlike mass and energy, exergy is not a conserved property. When matter or energy are transformed, exergy can be either transferred to other resources and/or eventually even be completely lost if dissipated instead of performing work.

Exergy provides a useful common metric for comparing different energy resources (e.g. electricity and heat) and for expressing environmental costs associated to the depletion of non-renewed stock resources. Exergy can measure resource consumption for well-defined thermodynamic processes involving exergy loss (e.g. heat transfer, mixing, unrestrained expansion, chemical reactions).

Being a function of the properties of a resource as well as of its reference environment, exergy is a logical measure when considering systems in direct interaction with their environment. For systems interacting with reservoirs other than their environment, second-law efficiencies can be directly determined without the need to define a standard reference environment.

Reference environment

Exergy as an indicator has added value when the performance of a system depends on the attributes of the environment. Moran and Shapiro (1998) apply the term environment to that portion of a system's surroundings for which its intensive properties are uniform and do not change significantly as a result of any process under consideration.

For buildings, communities and their associated energy systems, the reference environment can be taken as the outdoor air at the location of the building, as described in standard meteorological data sets.

Moran and Shapiro note that there is no one specification of the environment that suffices for all applications, and that extensive properties (internal energy, entropy and volume) may change as a result of interactions with other systems. For the sake of practicality, they idealise the environment as a system that is large in extent and uniform in temperature and pressure, assuming standard environmental conditions to be T_o=25ºC and P_o=1atm. This definition works well for systems operating relatively far from environmental conditions. However, variations in T_o and P_o may be not always be negligible relative to the system under consideration, and may need to be addressed in exergy calculations. Section 1.6 of this book further discusses determination of reference environments for building applications.

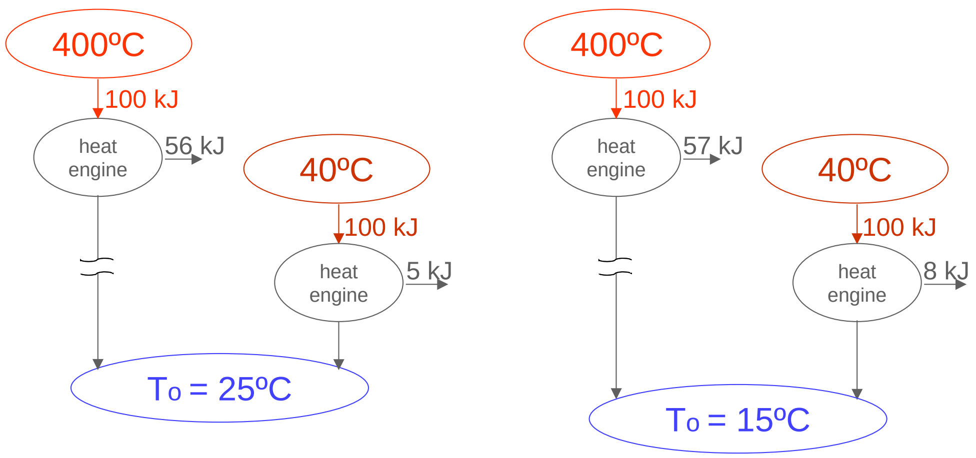

Figure 1: Environment temperature and its effect on exergy

Figure 1 illustrates the effect of environment temperature on the value of thermal exergy. When heat (e.g. 100 kJ) is supplied to an idealized heat engine at a temperature relatively far from the environment (e.g. 400ºC), lowering the reference temperature to from 25ºC to 15ºC results only in a marginal increase in the exergy output – in this case from 56 kJ to 57 kJ. On the other hand, when the same amount of heat is supplied much closer to environmental temperature (e.g. at 40ºC), lowering the reference temperature from 25ºC to 15ºC results in a much more significant increase in the exergy output – in this case almost doubling the exergy output from 5 kJ to 8 kJ.

For systems operating very near ambient conditions (e.g. buildings, district heating) the need to address local, seasonal and even daily changes in environmental conditions has been widely addressed, e.g. by Wall (1990), Shukuya (2004), Sakulpipatsin et.al. (2007, 2009) and Boelman et al (2009). For dynamic calculations, hourly values of outdoor air temperature T_o (where relevant also humidity W_o and possibly pressure P_o) characterize the reference environment. For steady-state or seasonally averaged calculations, suitable design values for T_o (also W_o, P_o where relevant) may be defined to characterize e.g. peak loads or cumulative demand over a given period.

Shukuya (2004) notes that, under specific circumstances, small variations in environmental conditions can even allow exergy to increase. For example, a mass of snow stored at temperature T in a well-insulated bunker would contain no thermal exergy in winter but would acquire cool exergy as environmental air temperatures (T_o) rise in spring and summer (see Figure 2). Sections 1.1 and 2.1 of this book address the definition and calculation of warm and cool exergy.

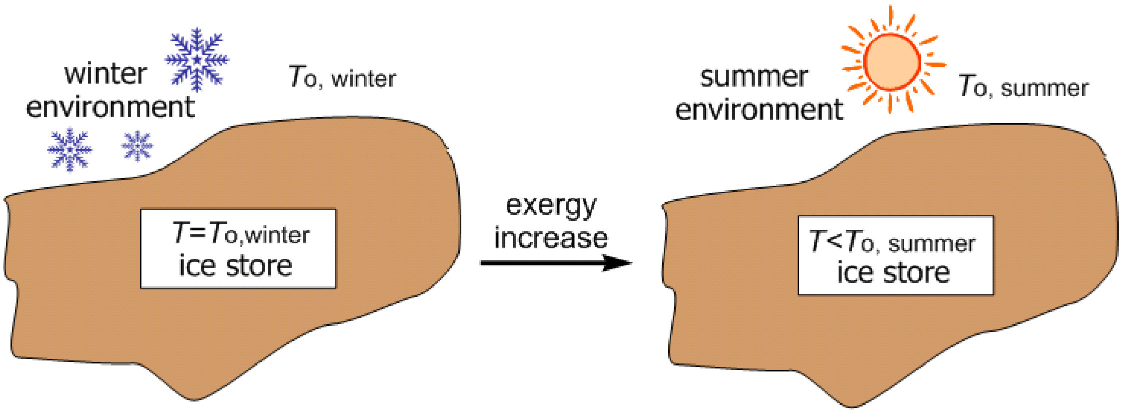

Figure 2: Environment conditions and their effect on exergy

Exergy as a work potential

Exergy can be regarded as a quality mark that can express the 'maximum available work or potential to perform work due to differences in pressure, temperature and composition between a system and its prevailing environment' (Swaan Arons et. al. 2004). This maximum refers to the amount of work that could theoretically be performed by bringing a resource into thermal, mechanical and/or chemical equilibrium with its surroundings through a reversible process.

The definition of exergy as a work potential is widely accepted, and has the advantage of unequivocally indicating the minimum amount of work needed to bring about changes in thermodynamic conditions of a system, relative to a pre-defined reference environment. Comparison of the theoretically minimum amount of work (required by an ideal, completely reversible process) with the work involved in a real process allows defining an unequivocal thermodynamic efficiency for a given process.

Thermodynamic efficiency

The thermodynamic efficiency (also known as second law or machine efficiency) is understood to be the ratio of the actual measured efficiency of a device to its maximum theoretical efficiency under the same conditions (Çengel and Boles 2002).

The thermodynamic efficiency of heat-driven devices depends on the heat source and heat sink temperatures (as stated by Carnot) and on how a device is engineered, but not necessarily on the environmental temperature. For example, when ground water is used instead of outside air as a heat source or sink, the thermodynamic efficiency can be determined without the environmental temperature. This may favour computational simplicity in dynamic calculations, since the ground temperature tends to be more stable than the environmental (air) temperature. In such cases, the stable underground surroundings can be regarded as a source of warm exergy in winter or of cool exergy in summer. Hence, the underground surroundings can be used as heat sinks or sources when the outdoor air is too warm or too cold to be used as such. Section 4.1 of this book cautions, however, about ground temperature variations caused by interaction with the building heating and cooling system.

Exergy efficiency

Energy-based efficiencies provide indications of how effectively exergy inputs are converted into exergy outputs, by indicating how much usable energy is delivered by energy transfer and conversion processes. Second-law efficiencies provide measures of how well a system approaches ideal reversible operation.

Swaan Arons et.al. (2004) note that efficiency values are easy to handle but can be misleading because they can be defined in numerous ways. Dincer and Rosen (2007) also note that sometimes confusion can arise when using exergy efficiencies, in part because several exist and these must be well understood before being used. Exergy efficiency has been extensively discussed in the literature, e.g. by Alefeld (1988), Tsatsaronis (1993 and 2002), Kotas (2001), Woudstra (2002) and Boelman et.al. (2009).

Rational (or functional) exergy efficiency is defined by a ratio of net exergy transfers: exergy of the product and exergy of the source(s). The rational exergy efficiency is normally adopted when the useful products (net outputs) and relevant sources (net inputs) can be unequivocally defined. By clearly defining relevant flows and eliminating by-products, losses and wastes, this definition has the advantage of being sensitive to changes in operating parameters (e.g. temperatures) as discussed in the literature (Semenyuk, 1990; Hirs, 2003; Boelman et al, 2009). On the other hand, the rational exergy efficiency requires judgment on what are products, sources, by-products, losses and wastes. This necessitates clear explanation of the underlying definitions and assumptions, and may limit the scope for comparison between different systems. Rational and simple exergy efficiencies are also discussed in section 1.3 of this book.

Simple (or universal) exergy efficiency is defined by a ratio of gross exergy transfers: all exergy outputs and all exergy inputs. The simple exergy efficiency is the ratio of the sum of the exergy exiting to the sum of the exergy entering. By including by-products, losses and wastes, it has the advantage of being straightforward, clear and comparable among different systems. The disadvantages lie in the lower sensitivity to changes in operating parameters, and possibly in the very lack of judgment on the usefulness of the inputs and outputs.

Exergy as a dispersion potential

In addition to indicating a maximum work potential, exergy can also express and quantify a potential of energy and matter to disperse in the course of their diffusion into their environment (Shukuya and Hammache, 2002).

From a chemical industry perspective, Swaan Arons et al (2004) have stated that any real processes must consume exergy to proceed, and hence all our technological activities are bound by our ability to supply exergy to our processes. They propose using exergy flows to quantify process sustainability by means of parameters such as resource depletion time, abundance factors and environmental compatibility.

In an Industrial Ecology approach, Connelly and Koshland (2001) put forward ‘exergy removal’ as a uniform, non-resource specific measure of consumption that uses first and second law principles to account for transfers and for irreversible losses of resource quality. Also from an ecology perspective, Fraser and Kay (2002) make a distinction between energy degradation and energy dissipation, noting that energy dissipation is only one of many methods to degrade energy. They define energy dissipation as the loss in ability to do work due to entropy production (this can be related to a flow from the system – e.g. heat leakage), and energy degradation as a loss in ability to do work from the perspective of the system utilizing the energy (this can be regarded as a loss in quality of energy within the system, and thus not related to a flow from the system – e.g. quality loss due to friction leading to heat generation).

Shukuya’s definition of exergy as a dispersion potential allows focusing not only on devices and their efficiencies, but also on the possible environmental impact resulting from the dispersion of energy and matter in any real process. The ‘lost work’ resulting from the dissipation of energy to less useful forms of energy can provide valuable insight into the location, origin and nature of energy conversion inefficiencies, and how they can be alleviated. Shukuya articulates this ‘lost work’ in terms of entropy that has to be disposed of. He states that a certain amount of entropy is generated due to exergy consumption within the building envelope system. This generated entropy must be discarded from the building envelope system to the surroundings. He adds that the energy flowing out the building envelope is accompanied not only by a decreased amount of exergy but also by an increased amount of entropy. The exergy consumed is proportional to the entropy generated, the proportionality constant being the environmental temperature. Entropy flow from the system is in fact required to dispose of entropy generated within the system: when the entropy flow from the system is larger than the entropy flow into the system, the difference is equal to the entropy generated in the system.

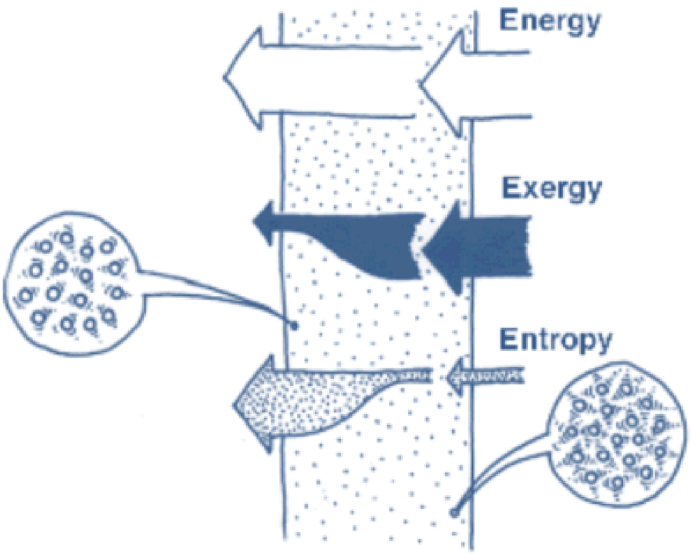

Figure 3: Energy, exergy, and entropy flows in and out a building envelope system (Shukuya, and Hammache, 2002)

Shukuya notes that disposing of the generated entropy from the system makes room for feeding on exergy and consuming it again, and that exergy is the concept to articulate what is consumed while entropy is what is disposed of. Exergy thus quantifies the potential of energy and matter to disperse in the course of their diffusion into their environment, while entropy quantifies the extent whereby the energy and matter in question are dispersed.

This approach considers both, how to make a system more efficient (by preventing the generation of avoidable waste streams) and how to dispose of these waste streams (so as to minimize their environmental impact).

Energy use and exergy consumption

Energy use can be understood as the sum of the energy inputs during conversion and distribution to provide a useful form of energy to the end-user, accounting for laws of energy and mass conservation. Exergy consumption refers to a decrease in the quality of energy available to perform a given task.

From an Industrial Ecology perspective, Connelly and Koshland (2001) note that consumption removes a resource’s exergy by transfer to other resources and by loss. This thermodynamic interpretation of resource consumption identifies exergy as being the resource quality that is lost during all forms of resource transformation. Exergy consumption can therefore, provide a basis for measuring the extent of resource degradation in a wide range of resource transformations.

Gößling-Reisemann (2008) stresses the need to conceptually differentiate between resource use and resource consumption. A resource (a material or energy flow) is used whenever it enters a system and then either leaves the system or is stored within it. Consumption occurs only when this flow is transformed inside the system, by changes in its quantity or quality. For example, a given amount of water used in different processes (e.g. in a hydro power plant, as a heat sink for a thermal power plant, for cleaning) may be conserved in terms of quantity even though its potential utility will decrease (e.g. by potential energy decrease, heat content increase, composition change). Unlike use, the notion of consumption can account for this decrease in potential utility. Entropy production might serve to measure real consumption covering the physical aspect of transformations.

Shukuya (2008) notes that the unique feature of the exergy balance equation is that there exists a term of 'exergy consumption'. This implies that a portion of exergy supplied from the source flowing into the system is necessarily consumed and thereby an amount of work, which is exergy itself, is extracted. In order for the state of a system to remain unchanged, it is necessary for the system to keep disposing of the generated entropy.

Exergy loss and resource depletion

Exergy loss refers to the destruction of exergy by irreversible processes occurring within a system and/or its immediate surroundings. Resource depletion refers to a decrease in quantity of a naturally occurring resource. Engineering literature often uses the term loss to generically designate flows that leave a system without having been (fully) utilized, whereas industrial ecologists may distinguish between concepts such as use, loss, depletion and consumption.

Gößling-Reisemann (2008) notes that the concept of depletion applies only to the materials found in nature, while the notions of use and consumption can apply to any form of material or energy. He adds that measuring resource depletion means focusing on the input side only, neglecting the transformations following the extraction. He also argues that depletion needs to be accompanied by other measures that allow for a more detailed look into these transformations, yielding insight into the causes for depletion and starting points for optimization.

Connely and Koshland (2001) note that in some consumptive processes (e.g. irreversible mixing) exergy is removed from the resources only by loss. In other processes (e.g. exothermal chemical reactions) exergy may be removed by transfer to other resources or by loss. They also use the term depletion to describe a second law phenomenon arising from irreversible loss of exergy, and note that consumption of non-renewed stock exergy causes resource depletion.

1.5.3 Approaches

System-centric approach

Fraser and Kay (2002) characterize the system-centric approach as internalizing all entropy production or exergy destruction processes, hence ignoring thermodynamic entropy production processes in the surroundings. They note that although this viewpoint acknowledges the important conclusion that entropy production is greater than or equal to zero locally, it does not possess the practical, or engineering, viewpoint incorporated into exergy. They mention a power plant example where ignoring entropy production in the immediate environment can lead to an incorrect optimum exhaust temperature.

Ecosystem-based approach

Another approach recognizes that there is entropy generation not only in the system but also in the immediate surroundings, and that something can possibly be done with exergy flows that exit a system. For example, the exiting energy may still have the potential to lift a weight, and the height whereby the weight can be lifted is determined primarily by the quality of energy rather than by its sheer magnitude. Fraser and Kay term this approach the isolated system viewpoint.

They adopt the isolated system viewpoint in their development of the exergy concept for analysis of ecosystems, noting that it represents an important paradigm shift from the system centric viewpoint. While the system-centric viewpoint internalizes all entropy production or exergy destruction processes, the isolated system maintains system boundaries, and makes processes in the local environment reversible by the addition of a reversible heat engine.

This approach implies that making all processes inside the system reversible is not necessarily sufficient to maximize the useful work, and that attention should be paid to making the processes in the immediate surroundings reversible.

Interaction between buildings and their immediate surroundings

Immediate surroundings are that part of the surroundings where the intensive properties are affected by processes taking place in the system. Environment is that portion of the surroundings that does not interact with the system and is free of irreversibilities, as explained above and in textbooks – e.g. Moran & Shapiro (1998), Çengel and Boles (2002).

This distinction is of key importance when considering systems operating very close to environmental conditions and exchanging energy and/or mass with their immediate surroundings, as illustrated in Figure 4.

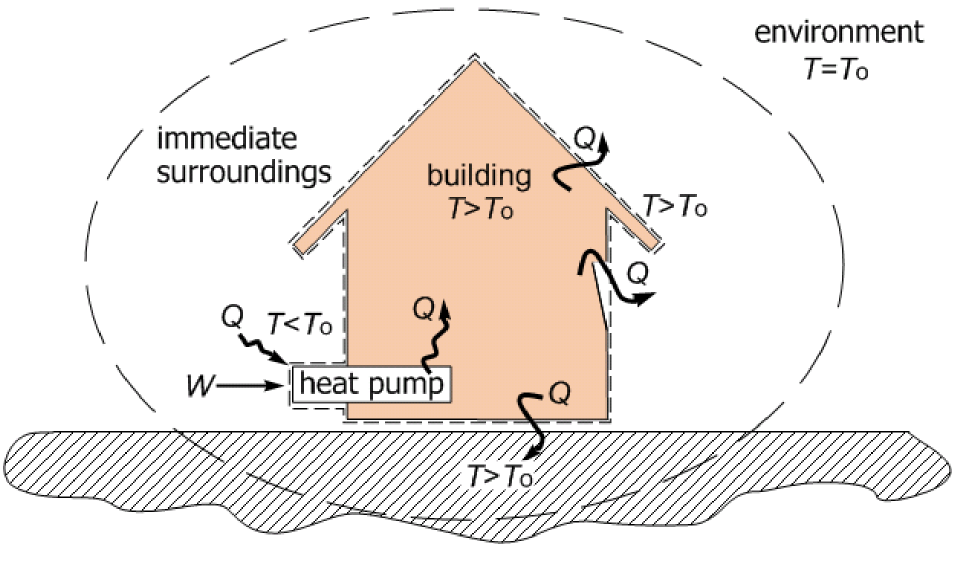

Figure 4: Environment and immediate surroundings of a building

In this simplified example, a heat pump uses electricity (*W*) to provide heat (*Q*) to a building, so as to maintain its temperature (*T*) above the environment temperature (T_o). The building loses some heat to its immediate surroundings, where the temperature is slightly above the environment temperature ($T>T_o$). There is also a heat pump extracting heat from outdoor air near the building, where $T<T_o$ very near the heat pump as a result of ambient heat extraction. A detached building in a sparsely populated area is likely to have a relatively small effect on its immediate surroundings.

On a larger scale, however, massive use of heating and cooling devices in densely populated urban areas may affect the nearby surroundings, as illustrated in figure 5.

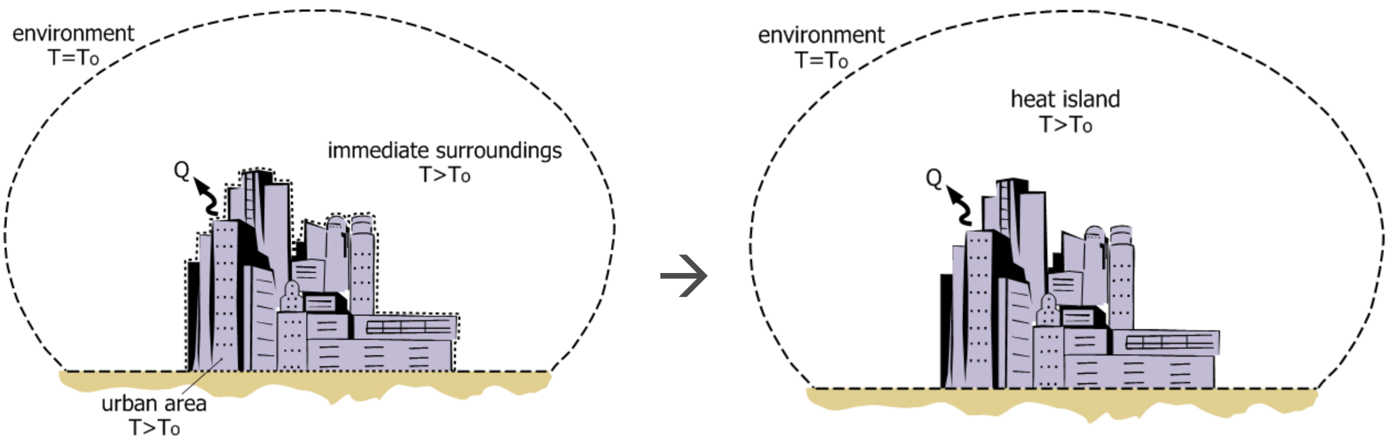

Figure 5: Heat islands around urban areas

Extensive use of air-source cooling devices in densely populated areas not only reduces the efficiency of the mechanical cooling cycles, but also increases their cooling loads. The use of ground-cooled air conditioning can alleviate this to a certain extent, as long as cooling loads are modest enough not to lead to significant underground heating – see section 4.1 of this book. In fact, public authorities in some countries (e.g. in The Netherlands) require balancing the amount of heat supplied to and extracted from an underground reservoir on a yearly basis.

From a resource preservation perspective, it is advisable to first reduce the cooling load as much as possible (by well-known design principles such as proper building orientation, sun shading and day lighting, night time ventilation and day/night heat storage within the building) and only use external energy resources (including the surrounding environment) for those energy loads that cannot be met otherwise. Building envelope design principles are well-established and have been described in many handbooks, e.g. by Oak Ridge (2006) and also as discussed in section 1.4 of this book. Regarding mechanical systems, it is important to not only use energy efficient components (e.g., pumps and fans), but also to design systems to avoid friction, mixing, unrestrained expansion and other exergy-dissipative processes.

Purchasing energy carriers to meet energy needs that could otherwise have been met using ambient energy sources entails an opportunity cost (Solberg, 2009). Depending on the scale of these sources, relative to the systems they serve, there may also be a (longer-term) environmental cost involved in using ambient sources, rather than reducing demand to avoid their use altogether. Examples of demand-reducing measures include absorbent paints, which could help reduce the heat island effect by mitigating cooling loads in buildings (and hence the need to dissipate heat into the environment) and also by reducing the amount of heat emitted by roofs to the immediate surroundings during daytime. Potential net energy savings from changing roof reflectivity have been reported by Lawrence Berkeley (2000), and cool roof working principles have been discussed among others by Oak Ridge (2005) national laboratories and in IEA context (Desjarlais and Scichili, 2007).

This simple example highlights the importance of moving away from end-of-pipe approaches toward preventative, design-oriented approaches of reducing not only demand but also waste flows, thereby reducing resource depletion and environmental degradation.

1.5.4 Conclusions

Exergy analysis can be used to improve the efficiency of systems, as well as the overall effectiveness of resource use within and outside the system. While each of these perspectives tends to be emphasized by different professions, energy systems in buildings and communities are in fact as much related to system efficiency as to resource use effectiveness.

Because energy systems in buildings and communities operate much closer to environmental conditions than many other applications (e.g. high-exergy industrial processes), thoroughly understanding and adequately describing system-environment interactions is of high importance. This includes acknowledging temporal and spatial changes in the reference environment, as well as differences between immediate surroundings and environment, or between heat sink and environment. For buildings and their associated energy systems, the outdoor air is generally accepted to be the most relevant reference environment, and is therefore recommended.

From an energy supply perspective, it is important to maximize the output obtained from a given resource input, for example by improving the efficiency of a given process and/or by switching to inherently more efficient processes. Maximum theoretical efficiencies and improvement potentials based on the second law of thermodynamics are useful decision-support indicators for choosing between improving or reengineering processes.

Switching to renewable energy sources may reduce energy resource depletion in relative terms. However, if demand is left unmanaged, increased waste heat dissipation into the immediate surroundings may lead temperatures in that portion of the environment to rise beyond levels compatible with effective disposal of the waste heat. If left unchecked, this process can lead to extending the boundaries of the immediate surroundings and/or the extent whereby they are affected by the heat produced in the buildings.

An exergy-based design approach can help to better match energy demand and supply – in terms of both quantity and quality – and hence to improve the overall effectiveness of energy resource utilization.

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1.6 Calculation of the Exergy Value of Air in Buildings

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1.6.1 Introduction

The exergy calculation methods rely on several properties of the reference environment, like temperature, pressure and chemical composition. Most research related to exergy and buildings only takes into account the thermal exergy of air (Schmidt, 2004; Asada and Boelman, 2004; Shukuya and Hammache, 2002; Sakulpipatsin et al., 2006; Itard, 2005). Chemical exergy caused by differences in water vapour content between in- and outdoor air and mechanical exergy caused by pressure differences between in- and outdoor air are not taken into account. However, from the work of Wepfer et al. (1979), Szargut et al. (1988) and Nishikawa et al. (1997) it appears that these assumptions may lead to less accurate results. This section presents a detailed and complete calculation of the exergy value of air in buildings, considering the thermal, mechanical and chemical contributions.

1.6.2 Exergy of a substance: physical and chemical exergy

The magnitude of the exergy value of a substance can be regarded as the sum of the physical and chemical contributions. Physical exergy refers to the difference between the physical state of the system, at a certain pressure and temperature, and that of the reference environment. Chemical exergy refers to the difference in chemical composition of a system, at the reference temperature and pressure, compared to the reference environment.

Physical exergy

Physical exergy (Ex_{ph}) is equal to the maximum amount of mechanical work obtainable when a substance is brought from its initial state temperature T and pressure P, to the state of the reference environment defined by T_o and P_o. For a process that brings a mass stream, considered to be under steady state conditions, from the initial state to the state of the reference environment in a reversible way, with only heat exchange with the reference environment at T_0, the change in physical exergy (ΔEx_{ph}) can be calculated by using equation (1).

$$Ex_{ph} = nH\left(P,T\right) - nH_0\left(P_0,T_0\right) - T_o\left(nS\left(P,T\right) - nS_0\left(P_0,T_0\right)\right) + \sum_i \int_{inital}^{final} \delta W_i \qquad (1)$$

In equation (1) n is the number of moles considered, nH is the enthalpy[2], nS is the entropy[3], δW_i is a small amount of work of type i. There can be many types of work, e.g. related to the force of gravity or mechanical forces. The subscript $_0$, indicates that the properties are in the state of the reference environment. Exergy calculations are generally performed under conditions, as is the case in normal applications in buildings, where the work terms can be ignored (Ahern, 1980). Equation (1) then reduces to equation (2) (Moran and Shapiro, 1998):

$$Ex_{ph} = nH\left(P,T\right) - nH_0\left(P_0,T_0\right) - T_o\left(nS\left(P,T\right) - nS_0\left(P_0,T_0\right)\right) \qquad (2)$$

Since the enthalpy (H) and the entropy (S) are dependent on temperature (T) and pressure (P), equation (2) can be expanded to equation (3).

$$Ex_{ph} = \left(\int_{T_0}^{T} \left(\frac{\partial nH}{\partial T}\right)_{P_0} dT + \int_{P_0}^{P} \left(\frac{\partial nH}{\partial P}\right)_{T} dP \right) - T_0 \left(\int_{T_0}^{T} \left(\frac{\partial nS}{\partial T}\right)_{P_0} dT + \int_{P_0}^{P} \left(\frac{\partial nS}{\partial P}\right)_{T} dP \right) \qquad (3)$$

For 1 mole of air it can very well be assumed that air in buildings is an ideal gas, hence the following expressions are valid:

$$\left(\frac{\partial H}{\partial T}\right)_{P_0} = c_p^{'} \; ; \left(\frac{\partial H}{\partial P}\right)_{T} = 0 \; ; \left(\frac{\partial S}{\partial T}\right)_{P_0} = \frac{c_p^{'}}{T} \; ; \text{ and } \left(\frac{\partial S}{\partial P}\right)_{T} = -\frac{R}{P} \qquad (3a)$$

$c_p^{'}$ and R are the molar isobaric heat capacity and the universal molar gas constant respectively. The molar physical exergy value ($ex_{ph}^{'}$) follows from equation (4):

$$ex_{ph}^{'} = \int_{T_0}^{T} c_p^{'}\, dT - T_0 \left(\int_{T_0}^{T} \frac{c_p^{'}}{T} dT - R \int_{P_0}^{P} \frac{dP}{P} \right) \qquad (4)$$

In the most general case, $c_p^{'}$ is a function of the temperature T. For the purpose of calculating the exergy value of air in buildings at the temperature interval – 50^0C ≤ t ≤ 50^0C, the $c_p^{'}$ values can be considered reasonably constant - the inaccuracy is < 1%. Following this assumption, the molar physical exergy value with respect to the reference environment T_o and P_o is given by the following equation:

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[2] Enthalpy (H) is the sum of the internal energy of the system plus the energy associated with work done by and on that system which is the product of the pressure and volume.

[3] Entropy (dS) is defined as '$\delta Q_{rev}/T$', where δQ_{rev} is the amount of heat absorbed reversibly by the system at temperature T.

$$ex'_{ph} = c'_p\left(\left(T - T_0\right) - T_0 \ln\left(\frac{T}{T_0}\right)\right) + RT_0 \ln\left(\frac{P}{P_0}\right) \quad (5)$$

In equation (5), the first term in the large brackets and multiplied by c'_p can be referred to as a thermal exergy value ex'_{th}. The second term can be called the mechanical exergy value ex'_{me}, related to pressure differences.

Chemical exergy

Chemical exergy (Ex_{ch}) is equal to the maximum amount of mechanical work obtainable when a substance is brought from the state of the reference environment to the dead state by processes involving heat transfer and exchange of substances only with the dead state (Kotas, 1985; Rosen et al., 1997; Interduct, 2002; Wepfer et al., 1979; Szargut et al., 1988). This final state is called 'dead state', which means that all substances are in thermal, mechanical and chemical equilibrium in this state.

In most chemical applications the dead state is defined as: P_0 =101325 Pa and T_0 = 298.15 K. In addition, the Gibbs energy is minimal for this state when all kinds of transition are possible without any kinetic limitation between the substances present in the atmosphere, the seas, and the upper crust (100 m) of the earth.

In this paper P_0 and T_0 are taken as the actual air pressure and temperature of the surrounding air of the building considered. The exergy of the outdoor air, which is the reference environment at P_o and T_o, is assumed to be 0, this is in accordance with what is assumed for the atmosphere (dry air) at P_0 =101325 Pa and T_0 = 298.15 K. For all substances present in dry air, the exergy value is also assumed to be 0 in this mixed state. For the purpose of calculating the exergy of air in buildings, an extra assumption is that the exergy of humid air and of water in this mixed state at P_o and T_o is 0. Because of these assumptions the change in molar chemical exergy for a substance i from the composition of i in the air outside of the building to the composition of i in the building, also at P_o and T_o, is equal to the chemical component of the molar exergy of substance i because the molar chemical exergy of substance i in the mixed state in the air outside the building is 0. This is shown in equations (6a to 6c).

$$\Delta ex'_{ch,i} = ex'_{ch,i}(in\ the\ building) - ex'_{ch,i}(outside\ air)(= 0) \quad (6a)$$

and

$$ex'_{ch,i} = ex'_{ch,i}(in\ the\ building) = \Delta ex'_{ch,i} \quad (6b)$$

and

$$ex'_{ch,i} = \Delta ex'_{ch,i} = RT_0 \ln\left(\frac{y_i}{y_{i,0}}\right) \quad (6c)$$

where y_i is the mole fraction of the i-th substance in the air of the building. y_{i0} is the mole fraction of the i-th substance of the air in the direct surroundings of the building, and R is the universal molar gas constant (8.314 $Jmol^{-1}K^{-1}$).

1.6.3 Exergy of air in buildings

The molar exergy value of air in buildings can be calculated as the sum of its physical exergy and its chemical exergy (Wepfer et al., 1979; Smith et al., 1996; Interduct, 2002). For airtight, poorly ventilated and/or air-conditioned buildings, there may be differences in the mole fractions of water and carbon dioxide in the air in- and outside the building. Three contributions to the exergy of air can be distinguished: that of dry and carbon dioxide free air, that of water, and that of carbon dioxide. The physical exergy value ($ex'_{ph,air}$) of air can be calculated, making use of equation (5), and is given in equation (7):

$$ex'_{ph,air} = \left(\left(1 - y_{water} - y_{CO_2}\right)c_{p,dry,CO_2\,free-air} + y_{water}c_{p,water} + y_{CO_2}c_{p,CO_2}\right)\left(\left(T - T_0\right) - T_0 \ln\left(\frac{T}{T_0}\right)\right) +$$

$$+RT_0 \ln\left(\frac{P}{P_0}\right) \qquad (7)$$

where y_{water} and y_{CO_2} are the mole fractions of water vapour and carbon dioxide in the air in the building respectively. The $c_{p,i}$ values are the molar isobaric heat capacities of dry and CO_2-free air, water vapour, and CO_2 respectively, considered as constants (independent of T). These $c_{p,i}$ values are given in Table 1 for the temperature interval – 50 ^{0}C ≤ t ≤ 50 ^{0}C. Although the uncertainty in the isobaric heat capacity of carbon dioxide is relatively large, the physical exergy values of air are reasonably accurate due to the small value of the mole fraction of carbon dioxide. In 2011 $y'_{CO_2,0}$ = 0.00039157 mole CO_2 per mole dry air (NOAA Research, 2012).

Substance	$c'_p / \left(J / molK\right)$	$c_p / \left(J / kgK\right)$	**Uncertainty [%]**
CO_2 free dry air	29.15	1006.4	± 0.09
dry air	29.165	1006.7	± 0.05
water	33.48	1858	± 1
CO_2	35.9	816	± 6.5

Table 1: Constant molar and specific isobaric heat capacity values to be used for the calculation of the thermal part of the physical exergy value of air in buildings.

The molar chemical exergy of the air considered, can be calculated, making use of the molar chemical exergy values given in equation (6c), as shown in equation (8):

$$ex'_{ch,air} = RT_0\left(\left(1 - y_{water} - y_{CO_2}\right)\ln\left(\frac{1 - y_{water} - y_{CO_2}}{1 - y_{water,0} - y_{CO_2,0}}\right) + y_{water}\ln\left(\frac{y_{water}}{y_{water,0}}\right) + y_{CO_2}\ln\left(\frac{y_{CO_2}}{y_{CO_2,0}}\right)\right) \quad (8)$$

The molar exergy value of the air considered is the sum of the molar physical and chemical exergy values as given in equations (7) and (8), and is given in shorthand form in equation (9):

$$ex'_{air} = ex'_{ph,air} + ex'_{ch,air} \quad (9)$$

Eventually, other substances, not considered now, can be included in equations (7) and (8) analogous to dry and carbon dioxide free air, water, and carbon dioxide.

For the most accurate calculation, the building must be considered to be built up of smaller sections e.g. rooms. The total exergy of air in the building is then a summation of the exergy values of the air of all sections.

The reference conditions can in principle be different for all sections. For example, consider the determination of P_0 for each section. Determine the mean height of that section and add to that the distance between the level of the section and the mean sea level. P_0 must then be measured (determined) at that distance from the mean sea level. The other conditions can best be determined outside the building façade at the closest to the centre of the section considered.

The most frequently occurring case concerns (de)humidification of air in buildings. In this case only two substances are considered: dry air and water vapour. This leads to a simplification of both equations (7) and (8). In equation (7) the product of the mol fraction and the $c_p^{'}$ value of carbon dioxide plus the product of the mol fraction and the $c_p^{'}$ value of dry and carbon dioxide free air is equal to $\left(1 - y_{water}\right)c_{p,dryair}^{'}$. The last term in equation (8) is zero, as are the mole fractions of carbon dioxide in the first term. For humid air equation (7) can be reformulated to form equation (10):

$$ex_{ph,humidair}^{'} = \left(\left(1 - y_{water}\right)c_{p,dryair} + y_{water}c_{p,water}\right)\left(\left(T - T_0\right) - T_0\ln\left(\frac{T}{T_0}\right)\right) + RT_0\ln\left(\frac{P}{P_0}\right) \quad (10)$$

Also, for humid air equation (8) can be reformulated into equation (11):

$$ex_{ch,humidair}^{'} = RT_0\left(\left(1 - y_{water}\right)\ln\left(\frac{1 - y_{water}}{1 - y_{water,0}}\right) + y_{water}\ln\left(\frac{y_{water}}{y_{water,0}}\right)\right) \quad (11)$$

Because building engineers and designers prefer to use the humidity ratio W [kg water vapour/kg dry air] (ASHRAE, 1993) and kilograms instead of moles, the unit J/mol in equation (10) and equation (11) can be converted to J/kg as shown hereunder. The mole fractions of water vapour in air (y_{water}) and of dry air (y_{dryair}) are related to the humidity ratio *W.* The mole fraction of water vapour in humid air (y_{water}) can be expressed as a function of the humidity ratio *W* as shown in equation (12):

$$y_{water} = \frac{W}{W + \frac{M_{H_2O}}{M_{dryair}}} \tag{12}$$

The standard composition of dry and carbon dioxide free air can be derived from Szargut et al. (1988) and is given in Table 2.

Substance	**Ar**	**He**	**Kr**	**N_2**	**Ne**	**O_2**	**Xe**
Mole fraction	9.33398E-3	5.00E-6	1.0E-7	0.78064837	1.800E-5	0.20999356	9E-8

Table 2: Mole fractions of the substances present in standard dry and carbon dioxide free air.

The molar masses of all substances, assumed to be present in humid air (also containing carbon dioxide) are derived from CRC Handbook of Chemistry and Physics (1973-1974) and are given in Table 3.

Substance	**Ar**	**He**	**Kr**	**N_2**	**Ne**	**O_2**	**Xe**	**CO_2**	**H_2O**
Molar mass [g/mole]	39.944	4.003	83.80	28.016	20.183	32.000	131.30	44.011	18.016

Table 3: Molar masses of the substances normally present in wet air.

From the data given in Tables 2 and 3 and the 2011 standard mole fraction of carbon dioxide in dry air it follows that $M_{dry\ and\ CO2free\ air}$ = 28.964 g/mole and that $M_{dry\ air}$ = 28.970 g/mole. The term $M_{H2O}/M_{dry\ air}$ in equation (12), can now be calculated and is 0.62189. Substitution of this value in equation (12) gives equation (13).

$$y_{water} = \frac{W}{W + 0.62189} \tag{13}$$

Substitution of equation (13) in equation (10) leads to equation (14).

$$ex'_{ph,humidair} = \left(\left(\frac{0.62189}{W + 0.62189} \right) c_{p,dryair} + \left(\frac{W}{W + 0.62189} \right) c_{p,water} \right) \left((T - T_0) - T_0 \ln\left(\frac{T}{T_0} \right) \right) +$$

$$+RT_0 \ln\left(\frac{P}{P_0}\right) \quad (14)$$

Substitution of equation (13) in equation (11) gives the transformed equation (15).

$$ex'_{ch,humidair} = RT_0\left(\left(\frac{0.62189}{W+0.62189}\right)\ln\left(\frac{W_0+0.62189}{W+0.62189}\right)+\frac{W}{W+0.62189}\ln\left(\frac{W}{W_0}*\frac{W_0+0.62189}{W+0.62189}\right)\right) \quad (15)$$

In order to determine the specific gas constant of humid air ($R_{humidair}$), first, the molar mass of humid air ($M_{humid\ air}$) must be calculated by using equation (16).

$$M_{humidair} = \sum_i y_i M_i \quad (16)$$

The mole fraction of dry air can be written as follows by making use of equation (13):

$$y_{dryair} = 1 - y_{water} = \frac{0.62189}{W+0.62189} \quad (17)$$

Substitution of equations (13) and (17) in equation (15) gives equation (18).

$$M_{humidair} = \frac{W}{W+0.62189}*M_{water}+\frac{0.62189}{W+0.62189}*M_{dryair} \quad (18)$$

Equation (18) can be simplified and, by introducing the numerical value of the molar mass of water, changed into equation (19).

$$M_{humidair} = \frac{W+1}{W+0.62189}*M_{water} = \frac{W+1}{W+0.62189}*18.016 \quad (19)$$

In order to express the physical and chemical exergy values in J/kg instead of in J/mole, the $c'_{p,i}$ values must be multiplied with the number of $moles_i$/kg. The relevant specific c_p values are given in Table 1. Instead of the universal gas constant R the specific gas constant of humid air ($R_{humidair}$) must be used.

$$R_{humidair} = R\frac{1000}{M_{humidair}} = R\frac{1000}{18.016}*\frac{W+0.62189}{W+1} \quad (20)$$

Substitution of R = 8.314 J/moleK in the previous equation gives the following expression for the specific gas constant of humid air:

$$R_{humidair} = 461.5*\frac{W+0.62189}{W+1}\,[J/kgK] \quad (21)$$

Substitution of the specific isobaric heat capacity values and the specific gas constant of humid air in equation (14) provides the final form of the equation for the specific physical exergy expression:

$$ex_{ph,humidair} = \left(\left(\frac{0.62189}{W + 0.62189} \right) * 1006.7 + \left(\frac{W}{W + 0.62189} \right) * 1858 \right) \left((T - T_0) - T_0 \ln\left(\frac{T}{T_0} \right) \right) +$$

$$+461.5 * \frac{W + 0.62189}{W + 1} * T_0 \ln\left(\frac{P}{P_0} \right) \quad (22)$$

The final form of the expression for the chemical exergy is obtained by substitution of the specific gas constant instead of the universal gas constant in equation (15) and the result is given in equation (23).

$$ex_{ch,humidair} = 461.5 * \frac{W + 0.62189}{W + 1} * T_0 *$$

$$* \left(\left(\frac{0.62189}{W + 0.62189} \right) \ln\left(\frac{W_0 + 0.62189}{W + 0.62189} \right) + \frac{W}{W + 0.62189} \ln\left(\frac{W}{W_0} * \frac{W_0 + 0.62189}{W + 0.62189} \right) \right) \quad (23)$$

The total exergy value of humid air in buildings (per kilogram of humid air) can be calculated by summation of equations (22) and (23). This exergy value is a function of air temperature *T*, pressure P, and the humidity ratio *W* in the building and the air temperature T_0, pressure P_0, and the humidity ratio W_0 in the direct environment of the building considered.

ASHRAE (1993) recommends $c_{p,\mathrm{dryair}}$ and $c_{p,s}$ as constant values (1.006 $kJkg^{-1}K^{-1}$ for dry air and 1.805 $kJkg^{-1}K^{-1}$ for water vapour). However, the molar isobaric heat capacity $c'_{p,i}$ is a function of temperature. In this section, mean isobaric heat capacity values, that can be applied in the temperature interval – $50^0C \leq t \leq 50^0C$, have been calculated making use of the molar isobaric heat capacities as function of T, as shown in equation (24) and making use of the data from Table 4.

$$c'_p = \sum_i y_i A_i + \sum_i y_i B_i * T + \sum_i y_i C_i * T^2 + \sum_i y_i D_i * T^3 \quad (24)$$

where A, B, C, and D are constants, and for a homogeneous ideal gas mixture a function of all y_i values. The coefficients for all components of dry and carbon dioxide free air, of dry and carbon dioxide free air itself, of carbon dioxide, of dry air, and of water are shown in Table 4.

Substance	A_i [J/moleK]	B_i [J/moleK^2]	C_i [J/moleK^3]	D_i [J/moleK^4]
Ar	20.80	0	0	0
He	20.80	0	0	0
Kr	20.80	0	0	0
N_2	31.15	-1.357E-2	2.680E-5	-1.168E-8
Ne	20.80	0	0	0
O_2	28.11	-3.680E-6	1.746E-5	-1.065E-8
Xe	20.80	0	0	0
CO_2free dry air	30.415	-1.059E-2	2.459E-5	-1.135E-8
CO_2	19.80	7.344E-2	-5.602E-5	1.715E-8
Dry air	30.411	-1.056E-2	2.456E-5	-1.134E-8
H_2O (ig)	32.24	1.924E-3	1.055E-5	-3.596E-9
H_2O (l)	72.432	1.0393E-2	-6.651E-6	0

Table 4: Coefficients A_i, B_i, C_i and D_i from equation (24) to calculate the molar isobaric heat capacities as a function of T for all substances present in humid air, for carbon dioxide free dry air, for dry air, and for water in the liquid phase (l). Data obtained from Reid et al., 1987.

The relative humidity, *RH*, defined as the ratio of the partial pressure of water and the saturated vapour pressure at the same temperature, can be determined experimentally. This in turn enables the calculation of W. For this calculation the saturated vapour pressure at the considered temperature must be known. This saturated vapour pressure can be obtained from the relation given in equation (25).

$$\frac{dP}{dT} = \frac{\Delta_{vap} S}{\Delta_{vap} V} \qquad (25)$$

$\Delta_{vap} S$ and $\Delta_{vap} V$ are the differences in molar entropy and volume between the molar values of the vapour and the liquid phase respectively. On the temperature interval $0^0C \leq t \leq 50^0C$ the following is a very good assumption:

$$\Delta_{vap} V = V_{(g)} = \frac{RT}{P} \qquad (26)$$

At saturation, the vapour phase and the liquid phase are in equilibrium. In this equilibrium state equation (27) holds:

$$\Delta_{vap}G = 0 \tag{27}$$

Under these conditions $\Delta_{vap}G$ can be written as given in equation (28):

$$\Delta_{vap}G = 0 = \Delta_{vap}H - T\Delta_{vap}S \tag{28}$$

From equation (28) it follows that $\Delta_{vap}S$ can be written in the form shown in equation (29):

$$\Delta_{vap}S = \frac{\Delta_{vap}H}{T} \tag{29}$$

In the temperature interval considered, $\Delta_{vap}H$ must be seen as a function of T:

$$\Delta_{vap}H(T) = \Delta_{vap}H(298.15) + \int_{298.15}^{T} \Delta_{vap}c_p \, dT \tag{30}$$

$\Delta_{vap}H(298.15) =$ 44004 J/mole and is obtained from the Steam Tables (ASME Steam Tables). $\Delta_{vap}c_p(298.15) =$ -41.284 J/moleK. This value is calculated from the isobaric heat capacity data for water(ig) and water(l) from Table 1. After substitution of this numerical data in equation (30), and of equation (30) and (26) in equation (25), equation (31) is formed.

$$\frac{dP}{dT} = \frac{P}{RT} * \left(\frac{44004 + 41.284 * (T - 298.15)}{T} \right) \tag{31}$$

Integration of equation (31) from P(298.15) to P(T) leads to equation(32):

$$\ln\left(\frac{P(T)}{P(298.15)}\right) = \frac{-31695}{R} * \left(\frac{1}{T} - \frac{1}{298.15}\right) - \frac{41.284}{R}\ln\left(\frac{T}{298.15}\right) \tag{32}$$

Substitution of $P_{water}^{sat}(298.16)$ = 3166 Pa, at the triple point of water, (from the Steam Tables (ASME Steam Tables)) and of R = 8.314 J/moleK in equation (32) results in, after rearrangement, the final equation (33). From this equation the saturated vapour pressure of water in Pa can be determined.

$$\ln\left(P_{water}^{sat}(T)/Pa\right) = 59.070 - 4.9656\ln(T) - \frac{6773.3}{T} \tag{33}$$

The saturated vapour pressure of water, expressed in Pa, is indicated by $P_{water}^{sat}(T)$. The inaccuracy in the saturated vapour pressure from equation (33) is less than 0.1%. At a total air pressure P and temperature T, the relative humidity is then defined as:

$$RH \equiv \frac{y_{water}P}{P_{water}^{sat}(T)} \tag{34}$$

When the RH value is determined (by experiment), the only unknown variable y_{water} can be calculated from equation (35):

$$y_{water} = \frac{RH * P_{water}^{sat}(T)}{P} \qquad (35)$$

Next, the humidity ratio W can be calculated by rewriting equation (12) as is shown in equation (36).

$$W = \frac{y_{water} M_{H_2O}}{(1 - y_{water}) M_{dryair}} \qquad (36)$$

For temperatures < 0^0C, liquid water becomes unstable with respect to the formation of solid water (ice). From a theoretical point of view it is then better to define the relative humidity as the ratio of the partial pressure of water in humid air and the saturation pressure of ice as shown in equation (37).

$$RH \equiv \frac{y_{water} P}{P_{ice}^{sat}(T)} \qquad (37)$$

Analogous to the derivation given to determine the saturation pressure of liquid water as a function of T, and making use of the value $P_{water}^{sat}(298.16)$ = 3166Pa, at the triple point of water, and of the sublimation pressure data given in CRC Handbook of Chemistry and Physics (1973-1974), equation (38) has been derived.

$$\ln\left(P_{ice}^{sat}(T) / Pa\right) = 33.5889 - 0.71602 \ln(T) - \frac{6325.3}{T} \qquad (38)$$

For the calculation of the specific exergy value of humid air in the temperature interval - 50^0C ≤ t ≤ 0^0C equation (38) has an inaccuracy < 0.1%. When the RH at T is known, the mole fraction of water in humid air, under these conditions, can be calculated from equation (37) and the humidity ratio W can be calculated by making use of equation (36).

Finally, the specific exergy value (J/kg) of humid air can be determined by summation of the specific physical exergy value and the specific chemical exergy value from equation (22) and equation (23) respectively.

1.6.4 Calculation examples

As a first example, the specific exergy of air in buildings in Lisbon at the first hour of the Typical Meteorological Year (TMY) reference year is calculated (Sakulpipatsin et al., 2009). The outdoor climate data is taken from the TMY2 data (NREL, 1995): T_o = 287.15 K, W_o = 0.00722, P_o = 101100 Pa. In the first example the indoor air conditions are assumed to be: T= 293.15 K, RH = 0.80, P = 101100 Pa.

Because the air pressure is the same in- and outside the building, the mechanical (related to pressure) part of the specific physical exergy of the air in the building, as given in equation (22), will be 0.

The thermal (related to differences in temperature) part of the specific physical exergy of air in the building, making use of the temperatures given, can then be calculated from equation (22). The result is: $ex_{Ph,Th}$ = 63.2 J/kg. The specific chemical exergy, which can be calculated with equation (23), is: ex_{ch} = 153.7 J/kg. The specific exergy of humid air is the sum of the contributions calculated before: ex = 216.9 J/kg.

In the second example the assumed indoor conditions are now different from the first example, with respect to the pressure: P = 101000 Pa instead of P = 101100 Pa.

The thermal part of the specific exergy of humid air in the building is now: $ex_{Ph,Th}$ = 63.2 J/kg: the same value as in the previous example.

Due to the difference in air pressure in- and outside the building, there is now a mechanical part of the specific physical exergy of humid air in the building. The value is: $ex_{Ph,Me}$ = -8.2 J/kg. This negative value indicates that ideal work must be done to realize a pressure $P < P_0$ inside the building. Normally this situation is realized by mechanical ventilation. In the reverse case, when $P_0 < P$, ideal work can, in principle, be obtained and the mechanical part of the specific physical exergy will be positive.

The specific chemical exergy will be a little bit different from the value calculated for the first example because when P is different y_{water} will be different too: ex_{ch} = 153.8 J/kg.

The specific exergy of humid air is the sum of the contributions calculated before: ex = 208.8 J/kg.

1.6.5 Defining the dead state for building applications

Because buildings and their associated energy and climate control systems operate at very-near environmental condition, exergy values become very sensitive to the designated reference conditions.

The dead state as considered in this section only concerns normal air in buildings (not containing e.g. formaldehyde) and exergy calculations for this air inside buildings. In this section not only one constant outside pressure is considered, but is some applications also the influence of gravity on the outside pressure is accounted for. Not all situations were considered at full length, but the most important are indicated. As mentioned in item 1.6.3 above, reference conditions may in principle be different for different rooms in a building. The temperature at different sides of the building can be different too and partly related to that also the relative humidity.

Essential is that the temperature, pressure and relative humidity of that portion of the outside air closest to that part of the building considered are the characteristic parameters of the dead state of that part of the outside air.

Dead state in buildings and in the chemical process industry

The main differences between the dead state considered in the chemical process industry and in the cases discussed in this section are:

Chemical process industry:

- P_0 = 0.101325 MPa;
- T_0 = 298.15 K;
- Water is treated in a special way: its chemical exergy value is related to water in mean sea water and a mean relative humidity.
- For all other components of air, they are assumed to be at the partial pressures determined by P0, the vapour pressure of water at the conditions mentioned, and the relative molar ratios of the components of dry air. In this mixture the chemical exergy values of air and all its components in the mixed condition are assumed to be zero.

For buildings:

- P_0 is the actual pressure of air outside the building.
- T_0 is the actual temperature of air outside the building.
- For both P_0 and T_0, further details may be necessary.
- For outside air and its normally occurring components (the same as in the chemical process industry) the chemical exergy is considered (defined) to be zero.

1.6.6 Conclusions

The air quality in buildings is of high importance. Hence, using appropriate calculations in an exergy analysis of air in a building is of importance. Due to the relatively large influence of the environment on the exergy value of air in the building, it is necessary to consider the environment as reference environment as is shown in this section. In most of the applications, e.g. in the chemical process industry, a dead state is defined at T_0 = 298.15 K and P_0 = 101325 Pa. Water is treated in a special way: its chemical exergy value of zero is related to water in mean seawater and a mean relative humidity value. In this dead state the exergy value of this air and of all other components of air are 0. In this section, the actual temperature and pressure of air outside the building are considered as the dead state. Hence, the exergy value for humid outside air and for all substances present in this humid air are assumed to be 0.

This section aimed at clarifying the fundamentals of moist air exergy calculations, and hence at lowering the threshold for building professionals to perform an exergy analysis and to interpret its results.

In the examples, a special condition of outside air is considered in combination with two different conditions of the air in the building. Depending on the temperature and humidity conditions of the air, the thermal and the chemical component of the exergy value can be of the same order of magnitude. This shows that only considering the thermal contribution, may lead to relatively large inaccuracy.

In the second example a mechanical contribution is introduced, and, as shown and interpreted, this contribution can be negative. In normal situations P and P_0 will often be nearly the same (even differing less than shown in example 2). If this is the case, then the mechanical contribution can be neglected compared to the thermal and the chemical contribution.

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Nomenclature

A_i	Coefficient in equation (24) [J/moleK]
Ar	Argon
B_i	Coefficient in equation (24) [J/moleK^2]
C_i	Coefficient in equation (24) [J/moleK^3]
c_p	Specific isobaric heat capacity [J/moleK]
CO_2	Carbon dioxide
D_i	Coefficient in equation (24) [J/moleK^4]
Ex	Exergy [J]
ex	Specific exergy [J/kg]
ex'	Molar exergy [J/mole]
H	Molar enthalpy [J/mole]
He	Helium
H_2O	Water

Kr	Krypton
M	Molar mass [g/mole]
n	Number of moles [-]
N_2	Nitrogen
Ne	Neon
O_2	Oxygen
P	Pressure [Pa]
R	Universal molar gas constant [J/moleK]
R_i	Specific gas constant of substance i [J/kgK]
RH	Relative humidity [-]
S	Molar entropy [J/moleK]
T	Temperature [K]
t	Temperature [ºC]
V	Molar volume [m^3/mole]
W	Humidity ratio [-] or work [J]
y_i	Mole fraction of substance i in the gas phase [-]

Subscripts

ch	Chemical
CO_2 free and dry air	Air without carbon dioxide or water vapour
Dry air	Air without water vapour
Humid air	Air with water vapour
i	Substance i
(ig)	Ideal gas phase
(l)	Liquid phase
me	Mechanical
o	Reference environment state; dead state

P	At constant pressure
ph	Physical
(s)	Solid phase
T	At constant temperature
th	Thermal
vap	Transition from (l) to (g) phase

Superscripts

‘	Indication of a molar quantity as difference between molar and specific quantities or as indication of the number of moles of CO_2 per mole dry air
sat	Saturated conditions, either (l)+(g) or (s)+(g) equilibrium

Abbreviations

TMY	Typical Meteorological Year

CHAPTER 2

METHODOLOGIES AND TOOLS FOR EXERGY ANALYSIS OF BUILDINGS

Introduction

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The application of the exergy method to the building sector, both at the envelope and services levels, is relatively new compared to the application to the power plant sector. Therefore, specific methodologies and tools are needed, as well as a demonstration of their use and potential.

In the first section of this chapter, Jansen and Torio investigate the issue of defining and calculating the building exergy demand. They define it as "the minimum amount of work needed to provide the energy demand". Following, they analyse two approaches to calculate the exergy demand: the "simplified" approach, considering exergy demand as exergy of heat to be delivered to or extracted from (termed 'cold') a conditioned space; and the "detailed" approach, where this lump demand is split between exergy of heat/cold at constant temperature and exergy of warm/cool air undergoing a temperature variation. They use basic equations and application examples to discuss their results of detailed exergy demand being lower relative to those obtained from the simplified procedure. This is because the quality factor of exergy related to mass transfer with a temperature gradient is lower compared to a similar exergy factor which accounts for only heat at a constant temperature. The difference between the results obtained using each of these approaches depends on the proportion of ventilation to transmission losses (or gains) in the building, as they show in some example cases.

While many tools for energy analysis of buildings are available, similar tools implementing exergy analysis at a building level are still lacking. A significant contribution in this regard is given by the Excel pre-design tool developed and described by Torio and Schmidt in the second section of this chapter. The tool allows evaluating exergy performance of a given heating system, taking into account the entire energy chain, from the primary energy transformation to the building envelope heat flows. By means of the spreadsheet software the most relevant exergy destructions can be identified and located. At the same time, alternative options satisfying the same heating demand of the building can be easily compared.

An example using the Excel pre-design tool is given by Schmidt in the third section of this chapter, where a "low exergy" benchmark for heating systems is proposed. The benchmarking methodology is based on the introduction of a new metric, namely the "exergy expenditure figure", taking into account the exergy consumption and the energy use of a given component. The closer the exergy expenditure figure is to the ideal limit, the more "LowEx" the component can be considered. Moreover, a limit to the exergy consumption of a building system is suggested, in line with the limits of the primary energy consumption that are already given in many European regulations. This shows how the exergy viewpoint can complement the energy one.

The Excel pre-design tool is based on two important hypotheses: the building exergy demand is calculated as exergy of heat transfer at constant temperature, and a steady state approach is adopted. The validity of the first assumption is discussed in the first section of the present chapter; the meaning and the validity of the latter are discussed in the last contribution to this chapter by Angelotti and Caputo.

Only a few examples of dynamic exergy analyses may be found in literature. However, if the outdoor environment is set as the reference state and energy flows in buildings are characterized by temperature levels near environmental temperature, the corresponding exergy flows may be very sensitive to the environmental dynamics. This presents a strong argument in favour of introducing dynamic exergy calculations. At the same time, performing dynamic exergy analyses will be time consuming, and an evaluation of when it would be worthy could be useful.

In the fourth section of this chapter, Angelotti and Caputo compare the results of stationary and dynamic exergy analyses applied to heating and cooling systems for buildings, in terms of exergy efficiency of some building climatisation systems. Their paper confirms that discrepancies between the two approaches are more important for cooling rather than heating, and in general in those conditions where the system is expected to be working for a small fraction of the time. Finally they show that care should be taken when comparing systems with similar performances, because using a steady rather than a dynamic exergy approach may influence the resulting performance.

The contributions collected here would naturally lead to the development of more accurate tools for exergy analysis of buildings, based on the detailed procedure for the calculation of the building exergy demand and performing dynamic simulations.

2.1 Exergy analysis of the demand for heating and cooling

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2.1.1 Introduction

Exergy analysis for the assessment of heating in the built environment has been an emerging field of science in the past two decades. Much work has been done by IEA ECBCS Annex 37 (Annex 37, 2003) and Annex 49 (Annex 49, 2011) and within the Cost Action C24 (C24, 2011), along with many scientific publications, several of which are discussed in Torío et al. (2009). Important for the exergy analysis of heating and cooling systems is the definition and calculation of the exergy demand for heating and cooling. The exergy demand can be defined as the theoretical minimum amount of work required to provide the required heating or cooling. In this section, the definition and calculation of the exergy demand is discussed, along with a detailed approach to determine this demand. An extended version of this section has been published in the final report of Annex 49 (Torío et al., 2011).

2.1.2 Definitions

Exergy can be defined as the maximum theoretical work that can be obtained from a quantity of energy or matter by bringing this energy or matter into complete equilibrium with a reference environment. The maximum theoretical work will be obtained if the considered energy or matter is converted in a system in which only reversible processes take place. The maximum amount obtainable is thus equal to the minimum amount of work required to realize the reverse process (Szargut, 2005).

Throughout this section the temperature of the surrounding outdoor environment (T_e) is regarded as the reference environment (T_0). For a more detailed discussion on the reference environment in building-related applications, Torío et al. (2009) and section 1.6 of this book can be consulted.

In thermodynamics heat is defined as the transfer of energy between two systems as a result of a difference in temperature. This energy is not related to matter. When analysing one system, heat is the transfer of energy across the system boundary at the temperature of the system boundary (T_b). According to the terminology commonly used by building professionals as well as in the international norm for calculation of the energy demand of buildings (ISO_13790, 2008), the term ‘heat’ is also used to refer to the ‘heat’ transferred with an amount of matter such as ventilation airflow ($m \cdot c_p \cdot \Delta T$). To distinguish between the two, this section uses the word 'sensible heat' to refer to the latter ($m \cdot c_p \cdot \Delta T$). For both concepts the symbol Q is used, in line with the aforementioned norm.

The sign convention used in this section is according to most textbooks on thermodynamics (Bejan et al. 1996; Moran and Shapiro 2004; Dincer and Rosen 2007):

- $Q > 0$ means heat transfer to a system;
- $Q < 0$ means heat transfer from a system.

The sign convention used in this section for exergy accompanying heat is:

- $Ex_Q > 0$ when exergy is transferred to the system;
- $Ex_Q < 0$ when exergy is transferred from the system

2.1.3 Energy demand and system boundaries

Definition of the energy demand

In this section the energy demand for heating and cooling is defined according to ISO_13790 (2008) as 'the heat to be delivered to, or extracted from, a conditioned space to maintain the intended temperature conditions during a given period of time'[1].This means that the demand is based on the characteristics of the building, the surrounding climate and the users (influencing ventilation requirements and internal gains). The total energy system for providing thermal comfort in the conditioned indoor spaces of a building clearly consists of the building itself *and* the building services or technical equipment to provide the heating or cooling. In the calculation of the demand however, the additional energy need introduced by the technical equipment is not included.

Energy demand calculation

The energy demand for heating and cooling is calculated on the basis of the energy balance of the building zone(s). No (de)humidification is regarded. The balance of the thermal zone(s) includes flows of energy (heat) and matter (ventilation and infiltration), which are listed below and illustrated in Figure 1:

- transmission: heat transfer through the building envelope between building zone and the outdoor environment;
- ventilation: the controlled supply and exhaust of ventilation air, which is the minimum amount of fresh air required by the use of the building;

[1] In ISO 13790 (2008) the term 'energy need' is used instead of 'energy demand', which is used in this section.

- infiltration: the uncontrolled inlet and exhaust of air through cracks of the building;
- solar gains: the heat gains from the sun that enter the zone(s) through transparent surfaces;
- internal gains: the heat gains from people, lighting and equipment within the zone(s);
- energy demand: the heat to be delivered to, or extracted from, a conditioned space to maintain the intended temperature.

NB. In this section a steady state calculation is assumed. This means that the outdoor conditions (temperature and solar irradiance) as well as indoor air temperature are assumed to be constant. Also, storage of heat into or release of heat out of the thermal mass of the building is not considered.

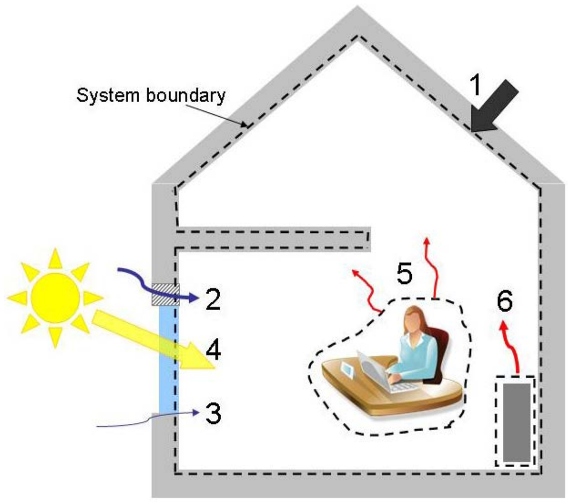

Figure 1: Flows of energy and matter across the system boundaries of the system "thermal zone(s) of the building".

The model used to calculate the energy balance is based on the following:

- a single zone model is assumed;
- the system boundaries for the determination of the energy demand enclose the air of the zone. The thermal mass of the surrounding surfaces as well as the people or equipment causing the internal heat gains or the equipment providing heating or cooling are outside the system boundaries;
- the temperature of the thermal zone is considered to be uniform, being the indoor air temperature.

Considering these assumptions, the system described above can be modelled as a control volume as shown in figure 2:

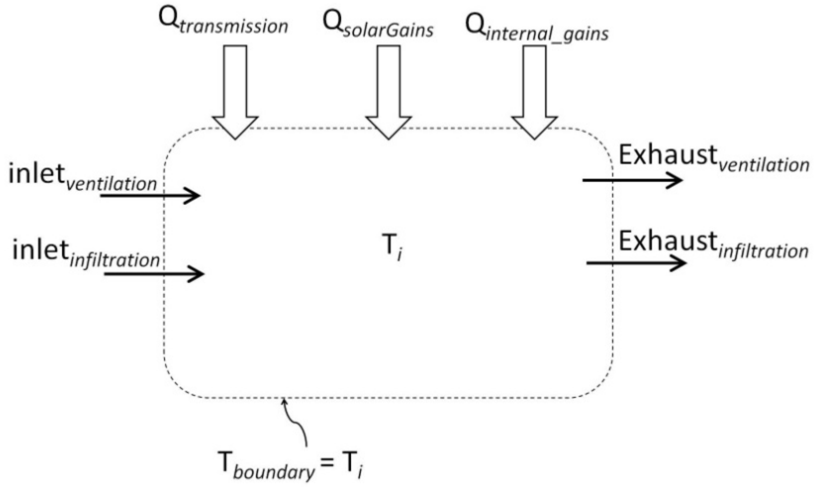

Figure 2: Scheme of the energy balance of a building's thermal zone, modelled as a control volume. Note: Q_{dem} is not indicated in figure 2.

Calculating the energy demand from the energy balance

The energy demand is calculated using an energy balance. In the energy balance as used in this section, all energy flows across the building boundaries are defined as a gain, having a positive value in case they represent an input and a negative value in case they are an output. Assuming the indoor air temperature to be equal to a chosen set point temperature, equation (1) can be used to calculate the heat demand, resulting in a positive value in case of heating (heat input), and a negative value in case of cooling (heat output). The energy balance for the indoor spaces of a building can thus be written as[2]:

$$\dot{Q}_{trans} + \dot{Q}_{vent} + \dot{Q}_{\inf} + \dot{Q}_{sol} + \dot{Q}_{\text{int}} + \dot{Q}_{dem} = 0 \tag{1}$$

The transmission heat gains are based on the weighted average heat resistance value [U-value] of the building envelope and the temperature difference according to equation (2):

$$\dot{Q}_{trans} = U \cdot A \cdot (T_e - T_i) \tag{2}$$

[2] In the equations used in this section the symbol $\dot{Q}$ (including a superscripted dot) is used, meaning all heat transfers are considered per second. For energy calculations related to buildings however usually a simple Q (without superscripted dot) is used, as often larger time-steps are used in energy balance calculations (like one hour or even a whole month).

The energy transferred with ventilation and infiltration air e.g. from inside to outside simplifies to the sensible heat transferred with the air according to equation (3)[3], since no (de)humidification is regarded.

$$\dot{Q}_{vent}, \dot{Q}_{\inf} = \dot{m} \cdot c_p \cdot (T_e - T_i) \quad (3)$$

Three energy demand situations to be distinguished

To determine the exergy demand of a heating or cooling demand (i.e. "the minimum amount of work required to provide an amount of heating or cooling"), three essentially different situations must be distinguished. In figure 3, the energy balances of these three situations are illustrated. They represent three different categories of situations that can occur in any kind of building. The exact building properties are not required for the purposes of this discussion, and the relevant data are described in Table 1:

Situation	T_e vs T_i	Gains vs losses	Resulting demand
1	$T_e < T_i$	gains < losses	Heating
2	$T_e < T_i$	gains > losses (*)	Cooling
3	$T_e > T_i$	Gains > losses	Cooling

Table 1: characteristics of three essentially different energy demand situations. (*)In this situation there is a cooling demand since internal and solar gains exceed transmission and ventilation and infiltration losses.

[3] No building services are included in the demand calculation, which means no preheating of ventilation air is assumed. Therefore the heat required to change the temperature of the air is based on the temperature difference between T_e and T_i.

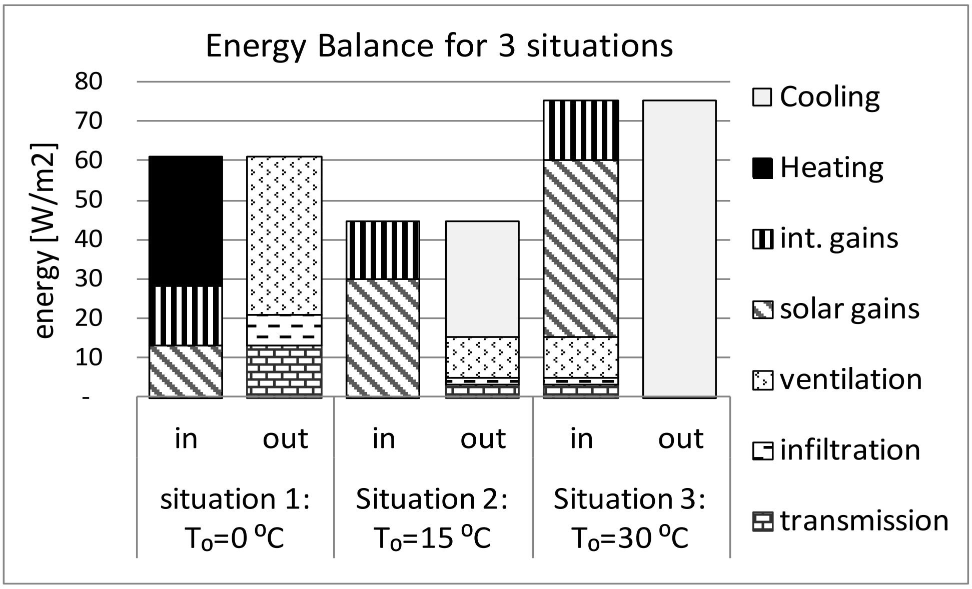

Figure 3: example of an energy balance for a standard office in three situations, resulting in heating (situation 1), or cooling (situations 2 and 3)

As can be seen, two types of cooling demand situations are defined. The difference between a cooling demand at $T_i > T_0$ (situation 2, which occurs due to relatively high internal and solar gains) and a cooling demand at $T_i < T_0$ (situation 3) is essential. In situation 2 the cooling demand can theoretically be provided by 'free' outdoor air, while in situation 3 active cooling is needed. For exergy calculation this difference becomes even more important, as will be explained in the following sub-sections.

2.1.4 Relevant exergy concepts for the calculation of the exergy demand

The exergy of heat

The calculation of the exergy of heat at constant temperature T (in Kelvin) is based on the ideal work output given a reversible thermal power cycle operating between the temperatures of the heat source and the environment. Background information on this can be found in various textbooks on thermodynamics such as Moran and Shapiro (2004). The exergy of heat can be calculated using equation (4).

$$Ex_Q = Q \cdot \left(1 - \frac{T_0}{T}\right) \qquad (4)$$

The factor $(1-T_0/T)$ is called the exergy factor of heat. It is also called 'quality factor' (Torío, Schmidt et al. 2011), or 'exergetic temperature factor' (Dincer and Rosen 2007). In Figure 4 the exergy factor of heat is shown for a given environmental temperature of 25 ^{0}C.

From figure 4, it can be seen that when T approaches infinity (a mathematical limit that cannot be reached), the exergy factor approaches unity, which means heat at very high temperatures can theoretically be totally converted into work.

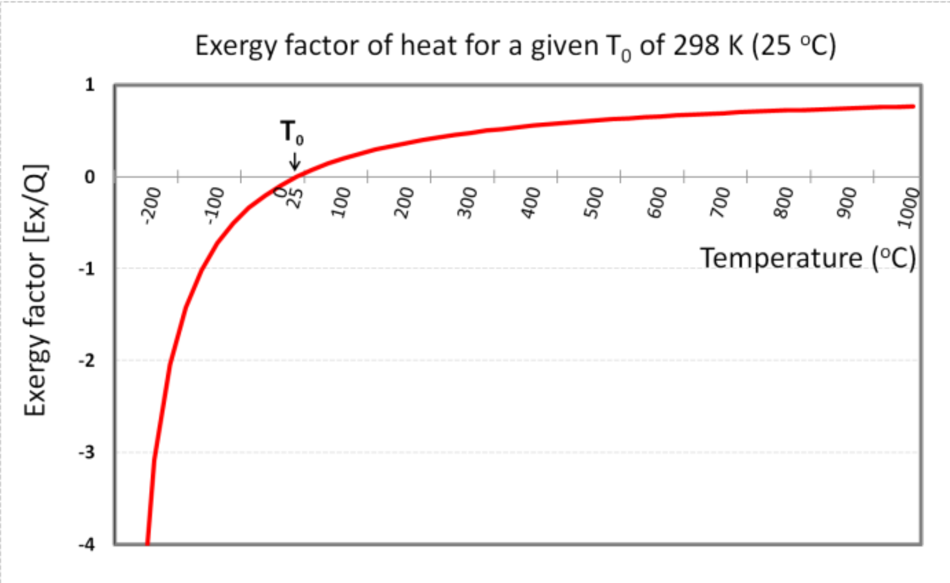

Figure 4: Exergy factor of heat

The exergy of cold and its relation to the direction of heat and exergy transfers

From equation 3 one sees that when $T<T_0$, the exergy factor has a negative value. As can be also concluded from equation (3), this implies that exergy and heat have opposite signs, and hence flow in opposite directions (see also Dincer and Rosen 2007) when $T<T_0$. The direction of the exergy transfer in relation to the direction of the heat transfer and the given temperatures is given and illustrated below. As can be seen from figure 5, the exergy transfer accompanying heat transfer takes place in the same direction as the heat transfer in case of $T>T_0$, and in the opposite direction of the heat transfer in case of $T<T_0$ (see also Jansen and Woudstra 2010). Section 1.1.3 of this book also discusses the concepts of warm and cool exergies as put forward by Shukuya.

- Heating a system (A) of which $T>T_0$ → energy input → (warm) exergy input
- Cooling a system (A) of which $T>T_0$ → energy output → (warm) exergy output
- Heating a system (B) of which $T<T_0$ → energy input → (cool) exergy output
- Cooling a system (B) of which $T<T_0$ → energy output → (cool) exergy input

The difference between the two cooling situations for the exergy demand calculations can be explained by looking at systems A and B in figure 5. When cooling system A (Q nr. 2), the exergy of the system decreases, meaning that in theory there is (warm) exergy present in the system. This cooling corresponds to situation 2 in figure 3. When cooling system B (Q nr. 4), the exergy of the system has to be increased, which means that (cool) exergy input is required (situation 3 of figure 3). It is important to take into account the direction (and hence the signs) of the heat and exergy transfer, in order to correctly assess the impact of a cooling demand of a building.

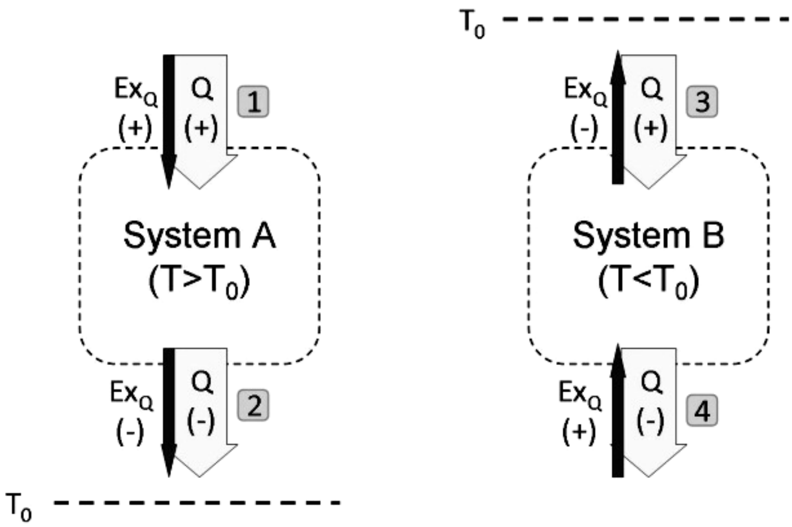

Figure 5: direction of the exergy transfer related to heat transfer and temperatures T and T_0

The exergy of an amount of ventilation and infiltration air

The exergy of an amount of matter can be defined as the amount of work that will be obtained from a system that brings the matter into equilibrium with the environment by reversible processes (Woudstra 2008).

The physical exergy (also called thermo-mechanical exergy, which is the part of the energy related to temperature and pressure) of an amount matter is calculated using equation (5).

$$Ex_{PH} = H - H_0 - T_0(S - S_0) \qquad (5)$$

Physical exergy can be divided into a temperature dependent part and a pressure dependent part. When considering only the temperature dependent part (as is the case for ventilation according to eq.(1)), and assuming a constant value for heat capacity at constant pressure c_p, the thermal component of the exergy of matter can consequently be calculated using equation (6) (adapted from Bejan, Tsatsaronis et al. 1996; Wall and Gong 2001; Szargut 2005).

$$Ex_{th,matter} = \int_{T_0}^{T} m \cdot c_p \cdot \left(1 - \frac{T_0}{T}\right) dT = m \cdot c_p \cdot \left(T - T_0 - T_0 \ln \frac{T}{T_0}\right) \quad (6)$$

When the energy balance is based on the (sensible) heat transferred across the system boundary, the calculation of the thermal part of the exergy of an amount of matter should preferably be on the basis of the amount of sensible heat Q. For this aim eq. (5) is converted and rearranged as shown in eq. (7).

$$Ex_{th,matter} = m \cdot c_p \cdot (T - T_0) \cdot \left(1 - \frac{T_0}{(T - T_0)} \ln \frac{T}{T_0}\right) = Q \cdot \left(1 - \frac{T_0}{(T - T_0)} \ln \frac{T}{T_0}\right) \quad (7)$$

Comparing the exergy of heat transferred at constant T and of sensible heat transferred with matter.

Since it is important for the determination of the exergy demand, figure 6 shows the difference between the exergy factor of heat and the exergy factor of 'sensible heat' as defined in this section. The exergy factor of heat is the factor in brackets in equation (4) and the exergy factor of 'sensible heat' is given between the large brackets in the utmost right part of equation (7).

Figure 6 shows that the exergy factor of heat at constant temperature T is larger than the 'exergy factor of sensible heat'. This can be explained by the fact that the temperature of the matter, which in the beginning is at temperature T, comes closer to T_0 while heat is being transferred. On the other hand, the heat transfer at constant T is, by definition, constantly available at T.

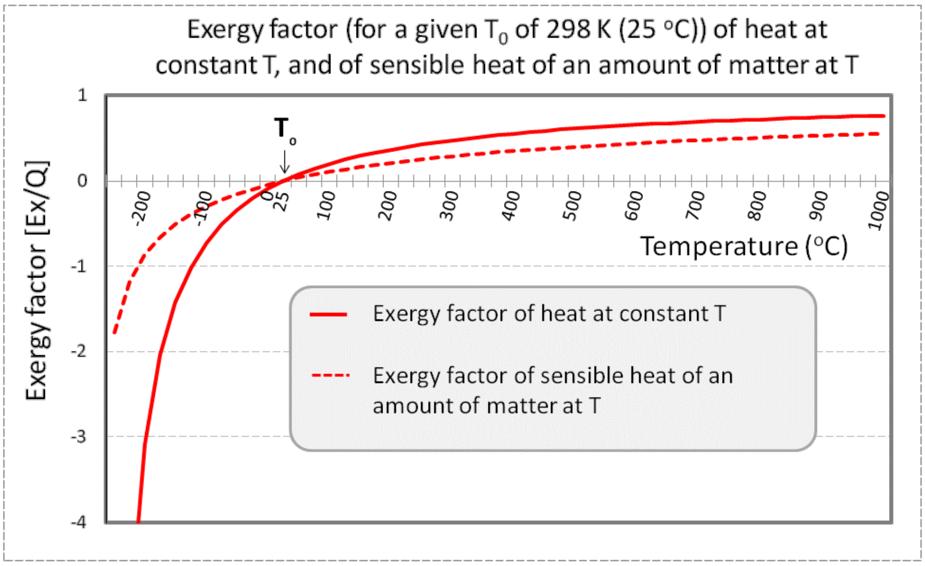

Figure 6: The exergy factor of heat at constant T (Ex/Q) and the exergy factor of sensible heat ($Ex/(m \cdot c_p \cdot \Delta T)$)

2.1.5 The exergy demand

The exergy demand can be defined as the exergy content of the energy demand, or the *minimum amount of work needed* to provide the required energy demand (input or output).

Simplified calculation of exergy demand

The simplified approach to calculating exergy demand which is usually used (Annex37; Schmidt 2004) assumes that, for heating and cooling demand, the required heat or cold is being provided at the indoor temperature T_i, as in equation (8).

$$Ex_{dem} = Q_{dem} \cdot \left(1 - \frac{T_0}{T_i}\right) \qquad (8)$$

In reality a temperature difference is required for heat transfer, but T_i represents the ideal limiting temperature at which heat can be supplied ($T \geq T_i$) or removed ($T \leq T_i$).

More detailed approach of calculating the exergy demand

The detailed exergy demand calculation presented in this section differentiates between exergy demand related to matter (air) and exergy demand related to heat. Most simply stated: When a building has no ventilation and only loses heat through transmission, all these losses need to be compensated for with an input of heat at least the indoor temperature or higher. Hence, the exergy of this demand can be calculated using equation (8) in this case. However: If a building loses no heat through transmission but only through ventilation, these losses can be compensated for by preheating the ventilation air. The exergy related to this preheating is calculated using equation (7). The heat losses can be similar for both cases, but the exergy (i.e. minimum work required to produce this heat) is different, as is shown in figure 6. Given an equal heat demand for the first and the second building, the exergy demand of the second building (having only ventilation losses and no transmission losses) will thus be lower than that of the first one.

In real buildings there are both transmission losses and ventilation losses, and also solar and internal gains, as can be seen from figures 2 and 3 showing the different energy ‘flows’ across the system boundary. The net heat demand covers the compensation of all losses minus the gains. This compensation is partly used to make up for heat losses related to ventilation and partly used to compensate for the remaining losses. The exergy demand for these more real cases is thus a bit more complicated to calculate. However, it can be concluded that in order to calculate the ideal exergy demand for heating (i.e. the *minimum* amount of work required) it should be assumed that in the first place the ventilation air is preheated; this can be maximally up to T_i and lower in case the net demand is lower than the ventilation losses. If additional heat is required, it should be assumed to be provided as heat at constant indoor temperature. This approach of calculating the exergy demand results in a lower demand than the approach mentioned above as ‘the simplified calculation of exergy demand’.

Basic examples to clarify the detailed exergy demand calculation approach

Below are three basic examples to demonstrate the detailed exergy demand calculation. All examples are based on the steady state analysis of a simple box with a volume (V) of 125 m^3, a total surface area (A) for transmission losses of 100 m^2 with a U-value of 0.3 W/m^2K, without windows. Outdoor temperature is equal to reference temperature (T_0) is 0^oC (273 K) and indoor temperature (T_i) is 20^0C (293 K). Steady state at one given time step is assumed upon calculating energy/exergy rates[4].

Example 1: Only transmission assumed (no ventilation, infiltration, solar or internal gains)

- Transmission gains = $U \cdot A\ (T_0 - T_i)$ = -600 W
- Net energy demand (heating) = 600 W

In this case all the heat is needed to compensate for transmission losses (at T_i), thus all the ideal heating has to be supplied at T_i. There is no fresh air intake (ventilation) thus no heat can be supplied to ventilation air. The exergy of the heat is:

- Exergy of energy demand (eq. 4) = 600·(1-273/293) = 41 W (Exergy factor 6,8 %)

Example 2: Transmission and ventilation assumed (no infiltration, solar or internal gains)

- Total transmission gains = $U \cdot A \cdot (T_0 - T_i)$ = -600 W
- Ventilation (0.1 kg/s) gains = $\dot{m} \cdot cp \cdot (T_0 - T_i)$ = -2000 W
- Net energy demand (heating) = 2600 W

Of this demand a maximum of 2000 W can be supplied to the ventilation air, which would then have temperature T_i. If more heat is supplied to the ventilation air, T would become higher than T_i, which means the exergy factor will become higher. The remaining 600 W needs to be supplied as heat at T_i. This means the demand is split in two:

- Exergy demand to heat ventilation air up to T_i (eq. 7) = 70 W
- Exergy demand for heat at T_i of energy demand (eq. 4) = 41 W

[4] The examples (especially 2 and 3) are meant to demonstrate that the minimum exergy demand can be achieved by assuming preheating (or precooling) of the ventilation air. In order to achieve preheating or precooling in a real situation, a technical component would be required, such as a heat recovery unit. This system will have to be evaluated when assessing the total energy system, but it is not included in the demand calculation according to the definition of the demand given in this section. The potential use of waste heat from the exhaust air is thus not considered as a reduction of the energy demand, but can be considered as a source when analyzing the heat recovery unit.

- Total exergy demand = 111 W (Exergy factor 4.3 %)

Example 3: Transmission, ventilation and internal gains assumed (no infiltration or solar gains)

- Total transmission gains = $U \cdot A \cdot (T_0 - T_i)$ = -600 W
- Ventilation (0.1 kg/s) gains = $\dot{m} \cdot cp \cdot (T_0 - T_i)$ =-2000 W
- Internal gains (1000 W assumed) = 1000 W
- Net energy demand (heating) = 1600 W

Of this demand a maximum of 1600 W can be supplied to the ventilation air. The resulting indoor temperature will then be sufficient. This means the air does not need to be preheated up to 20 °C, but up to T = 16 °C (T_0 + ΔT of (1600/2000)·20 °C = 16 °C), which on a Kelvin scale is 289 K. No additional heat at T_i is required. This means the exergy demand is:

- Total exergy demand (= exergy to heat ventilation air up to 16 ^{0}C (eq. 7) = 45 W (exergy factor = 2.8 %)

As can be seen from these simplified examples the exergy factor of the demand for each case is different, even though the T_0 and T_i are assumed to be equal. Using the simplified exergy demand calculation approach all cases will lead to the same exergy factor.

Equations to calculate the detailed exergy demand for heating

As demonstrated in the previous examples, the generally applicable approach and calculations for detailed exergy demand calculation are as follows for the case of a heating demand[5]:

First, the total heat demand ($Q_{dem,H}$) must be split up into a part that is a heat demand that can compensate for ventilation losses ($Q_{dd,vent,H}$, i.e. the part that can be achieved by preheating ventilation air according to equation 7) and a part that must compensate for additional heat losses ($Q_{dd,H}$, this part must be supplied at indoor temperature or higher, according to equation 8). Thus, the heat demand is split into these two parts as shown in equation (9):

$$\dot{Q}_{dem,H} = \dot{Q}_{dd,vent,H} + \dot{Q}_{dd,H} \tag{9}$$

Since the part that can compensate for ventilation losses requires less exergy, this part must be maximized: If the total ventilation losses are bigger than the heat demand, the total heat demand can be achieved by preheating ventilation air; if the ventilation losses are larger than the heat demand all the ventilation losses must be compensated for, according to equation (10)[6]:

[5] The exergy demand for cooling is not treated in this section, but can be calculated following the same reasoning, assuming precooling of ventilation air down to indoor temperature as much as possible (see also Torío et al. 2011).
[6] Note that ventilation heat transfer is defined as a positive value when it is a gain.

$$\dot{Q}_{dd,vent,H} = \max(-\dot{Q}_{vent,H}, \dot{Q}_{dem,H}) \tag{10}$$

The remaining heat demand – if still needed - results from equation 9.

To calculate the exergy of heat needed to preheat ventilation air ($Ex_{dd,vent,H}$), the required temperature is needed. If all ventilation losses need to be compensated for, the air needs to be preheated up to the indoor temperature. If the heat demand is smaller than the ventilation losses, the air needs less preheating. The temperature can be calculated using equation (11), and the exergy is then calculated using equation (12).

$$T_{dd,vent,H} = T_0 + (T_i - T_0) * \frac{\dot{Q}_{dd,dem,H}}{-\dot{Q}_{vent}} \tag{11}$$

$$\dot{E}x_{dd,vent,H} = \dot{Q}_{dd,vent,H} \cdot \left(1 - \frac{T_0}{T_{dd,vent,H} - T_0} \cdot \ln \frac{T_{dd,vent,H}}{T_0}\right) \tag{12}$$

For the exergy of the remaining heat demand, which needs to be supplied at indoor temperature or higher, the normal exergy factor (also given in equation 8) can be used as shown in equation (13):

$$\dot{E}x_{dd,H} = \dot{Q}_{dd,H} \cdot \left(1 - \frac{T_0}{T_i}\right) \tag{13}$$

The total detailed exergy demand for heating ($Ex_{,dd,H,tot}$) is then calculated using equation (14):

$$\dot{E}x_{dd,H,tot} = \dot{E}x_{dd,vent,H} + \dot{E}x_{dd,H} \tag{12}$$

Examples of differences between simplified and detailed exergy demand calculations

A steady state comparison of the simplified and the detailed approach has been performed for a simple office space model. The relevant data that relate to all alternatives are shown in table 2:

Building properties		
Office space, corner	5.40·5.40 m, height 3.00m	
Floor area	29	m^2
Closed exterior facade area	19.44	m^2
Total exterior glass surface	13	m^2
Infiltration rate	0.6	volume/h
Other data		
Internal gains	25	W/m^2
Solar irradiation for all windows	120	W/m^2
T_i	20 / 298	^oC / K
T_0	5 / 278	^oC / K

Table 2: building properties and energy data used for all case studies

Four variants are shown, assuming different air change rates and insulation values for this office space. The ventilation rate and average U values are chosen in such a way that the (steady state) energy demand is the same for all cases. These values are given in table 3.

Case	**Average U value (for total façade)** W/m^2K	**Air Change rate for ventilation** volume/h	**Energy demand** W/m^2
A	3.5	0.5	14
B	2.6	1.5	14
C	1.2	2.5	14
D	0.8	3.5	14

Table 3: Assumed U-value, air change rate and resulting energy demand per case

The resulting exergy demand according to the simplified and detailed exergy demand calculation are listed in table 4 and illustrated in figure 7.

Case	Exergy demand, simplified W/m²	Exergy demand, detailed W/m²	Exergy factor, simplified %	Exergy factor, detailed %
A	0.74	0.55	5.1	3.8
B	0.74	0.24	5.1	1.7
C	0.74	0.12	5.1	0.9
D	0.74	0.11	5.1	0.7

Table 4: Resulting exergy demand from simplified and detailed approach, per case

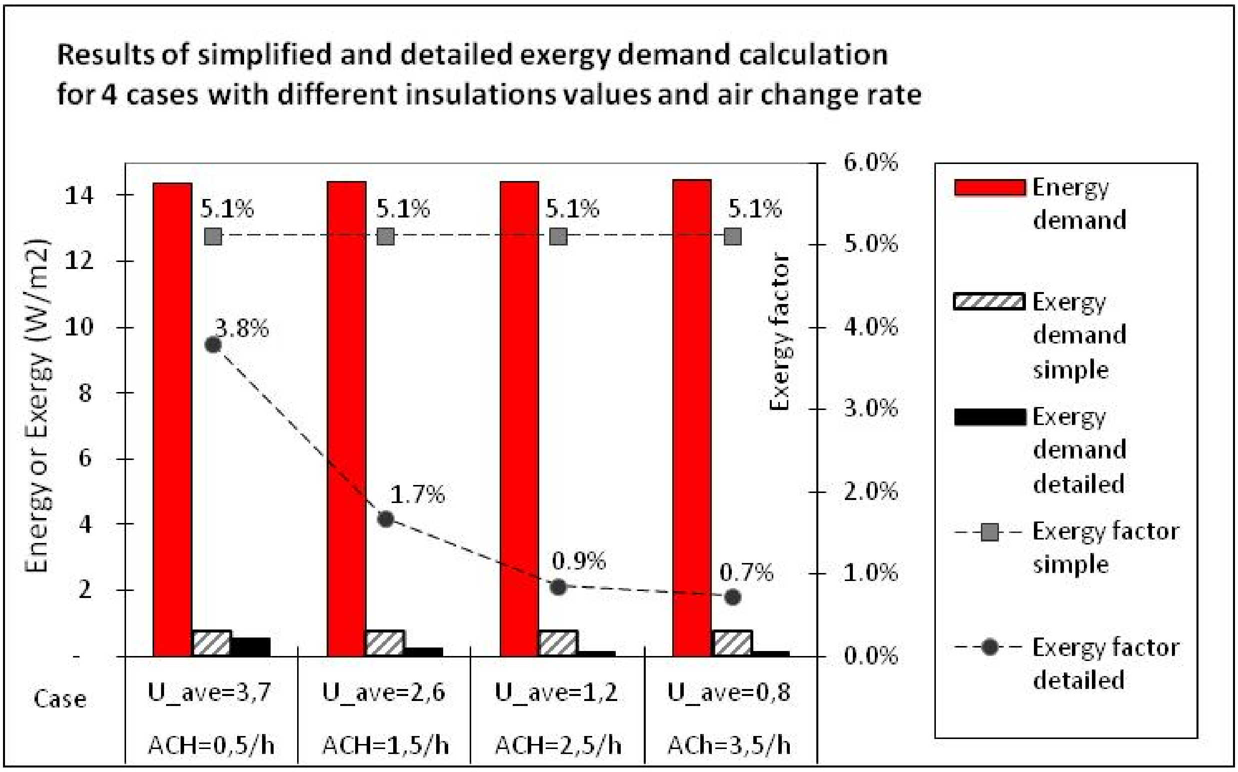

Figure 7: Results of the (steady state) simplified and detailed exergy demand calculations for four case studies with different insulation values and air change rates.

<u>Discussion of results</u>

- the exergy demand in all cases is much smaller than the energy demand. The ratio between the two is shown as the exergy factor of the demand.

- the detailed exergy demand (which is the sum of the demand related to ventilation air and the demand related to additional heat at T_i) is smaller than the exergy demand according to the simplified demand calculation.

- since the energy demand and the temperatures are equal for all cases, the simplified exergy demand is equal for all cases. However, due to the different contribution of ventilation and transmission losses the detailed demand differs for all cases.

- it is shown, that by decreasing transmission losses and increasing ventilation rates (and thus losses), the detailed exergy demand becomes smaller even though the energy demand is the same. This is due to the fact that if the contribution of ventilation losses is relatively big, a larger part of the heat demand can be achieved by preheating ventilation air.

From these cases it can be concluded that the ideal (minimum) demand depends not only on the indoor and outdoor temperatures and the resulting energy demand, but also on the relative contribution of ventilation losses to the total energy demand. This means that in theory it is more exergy efficient to preheat ventilation air (as far as needed but no further than indoor temperature), than to have air enter at outdoor temperature and supply all heating at indoor temperature. (This conclusions is logical, since the mixing of outdoor air with indoor air by definition involves mixing which causes exergy destruction).

Note: It should be noted that the *ideal minimum demand* is calculated, which is only based on the energy balance of the thermal zones and on the minimum amount of exergy required to heat ventilation air and supply heat at T_i. In practice this would mean the ventilation air must be preheated with a technical device, which can require the need for more fan energy. For the final analysis, the total heating or cooling system including all system components has to be assessed in order to take into account all exergy losses.

2.1.6 Conclusions

This section discussed the exergy demand for heating and cooling in buildings. Two critical issues for a better understanding of the exergy demand, defined as the 'minimum amount of work required to provide the needed heating or cooling' were discussed:

First, the essential difference between two situations with a cooling demand is discussed: 1) a cooling demand while $T_i>T_0$ and 2) a cooling demand while $T_i<T_0$ (this can occur due to solar and internal gains). In the first case the cooling demand in fact represents an exergy output (a need to dispose of unwanted 'warm exergy') in order to bring the system to a temperature closer to the environmental temperature. In the second case the cooling demand represents a required exergy input (which is a true exergy demand) since the system (indoor space) must be brought to a temperature further from the environmental temperature. It is therefore important to consider the direction of the heat and exergy transfer in order to correctly assess the exergy of a cooling demand. It means that in some cases a cooling demand ideally does not need an exergy input.

Secondly a detailed approach to calculate the exergy demand is demonstrated. The detailed exergy demand is the sum of the demand needed to preheat or precool the required ventilation air and possibly a remaining demand needed to compensate for transmission and infiltration losses. This approach for calculating the exergy demand results in a lower exergy demand than the approach currently applied (mentioned within item 2.1.5) since it assumes reduced mixing of colder (fresh) ventilation air with warmer indoor air and takes into account that reversible heating of ventilation air - from T_0 to T_i – requires less work than providing heat at a constant T_i. From this discussion it can be concluded that in theory it is more exergy efficient to preheat ventilation air (as far as needed but no further than indoor temperature), than to have air enter at outdoor temperature and supply all heating at indoor temperature. In practice the performance of the entire system of course depends on the actual HVAC components used.

Acknowledgement

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Nomenclature

A	Area [m^2]
c_p	Isobaric heat capacity [$Jkg^{-1}K^{-1}$]
Ex	Exergy [J]
ΔEx	Exergy difference [J]
H	Enthalpy [J]
m	Mass [kg]
$\dot{m}$	Mass flow rate [kg/s]
Q	Heat [J]
S	Entropy [J]
T	Air temperature [K; °C with notation]
U	Heat transfer coefficient [W/m^2K]
V	Volume [m^3]
W	Watt [J/s]

Subscripts

0	Reference environment
b	Boundary
C	Cooling
dem	Demand
dd	Detailed demand
e	Outdoor
H	Heating
i	Indoor
inf	Infiltration

int	Internal gains
Q	Heat
sol	Solar gains
th	Thermal
trans	Transmission
vent	Ventilation

Superscripts

.	Per second [1/s]

Abbreviations

COST	European Cooperation in Science and Technology
NL	Netherlands
EOS	(Dutch:) Energie Onderzoek Subsidie (Energy Research Subsidy)

2.2 Excel pre-design tool for exergy analysis of buildings

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2.2.1 Introduction

The Excel-based pre-design tool aims at increasing the understanding of the exergy flows within the built environment and at facilitating further improvements on the energy use in this sector. It is a simple and transparent tool which presents the exergy approach in an easy to understand and comprehensible manner for its users, including architects and construction engineers. The concept and structure of the tool are based on the Excel tool developed within the IEA ECBCS Annex 37 (it can be downloaded under www.lowex.net) and represent a further development of that tool.

The field of application is mainly focused on buildings with normal and low internal temperatures respectively, e.g. residential buildings, day-care facilities for children and office buildings. From the user, a definition of the building details (e.g. building envelope, air tightness, etc.) is required. By means of several drop-down menus, different building systems can be chosen to supply the required building demands. This allows limiting the required amount of input data. Energy calculations are based on the German energy saving Standard (EnEV, 2007) and follow a steady-state approach. A detailed description of the calculation method implemented in the tool can be found in IEA Annex 49 (2009).

2.2.2 Tool description

Exergy analysis is performed based on the stationary heat demand (Φ_h) calculated for a single representative moment for user-defined outdoor and indoor conditions, such as solar radiation, internal gains, and air exchange rate. Due to the inaccuracies of performing an annual exergy analysis based on steady-state conditions, and in order to avoid misinterpretation of the results, stationary analyses for representative points in time are preferred.

Structure

The calculation method is divided into the following blocks and subsystems (in direction of the energy flow):

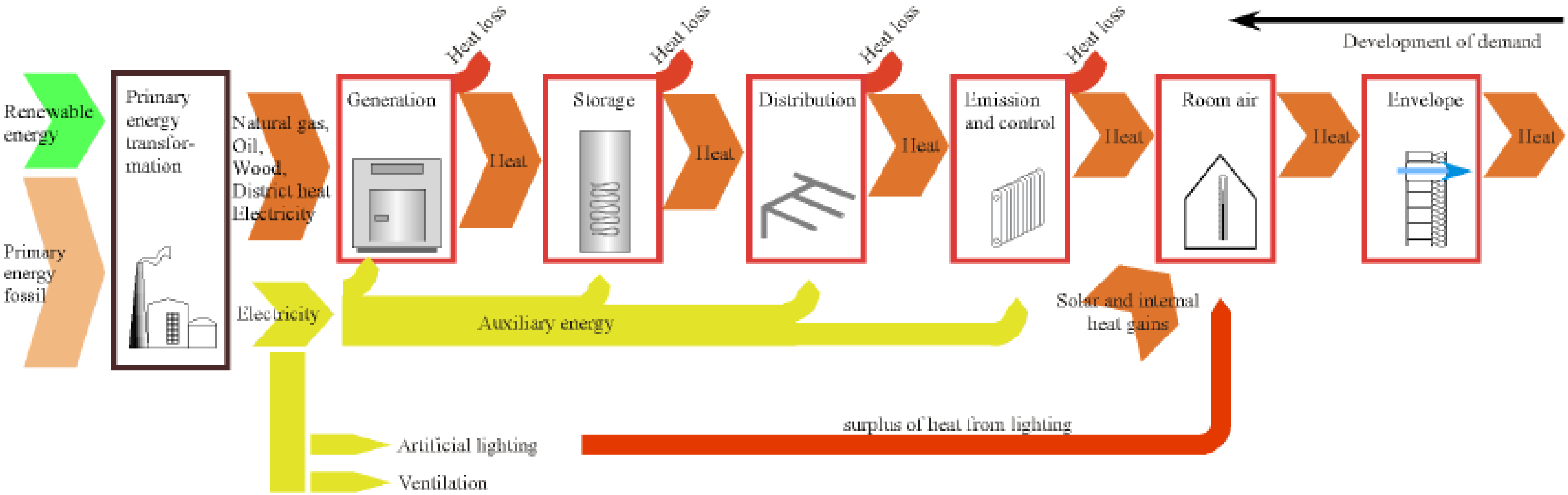

Figure 1: energy flows through a building how they are shown in the present tool. The energy flows are examined from the source until the building shell based on the DIN 4701-10 (2003).

Within the Tool it is possible to select and combine two different energy generation systems:

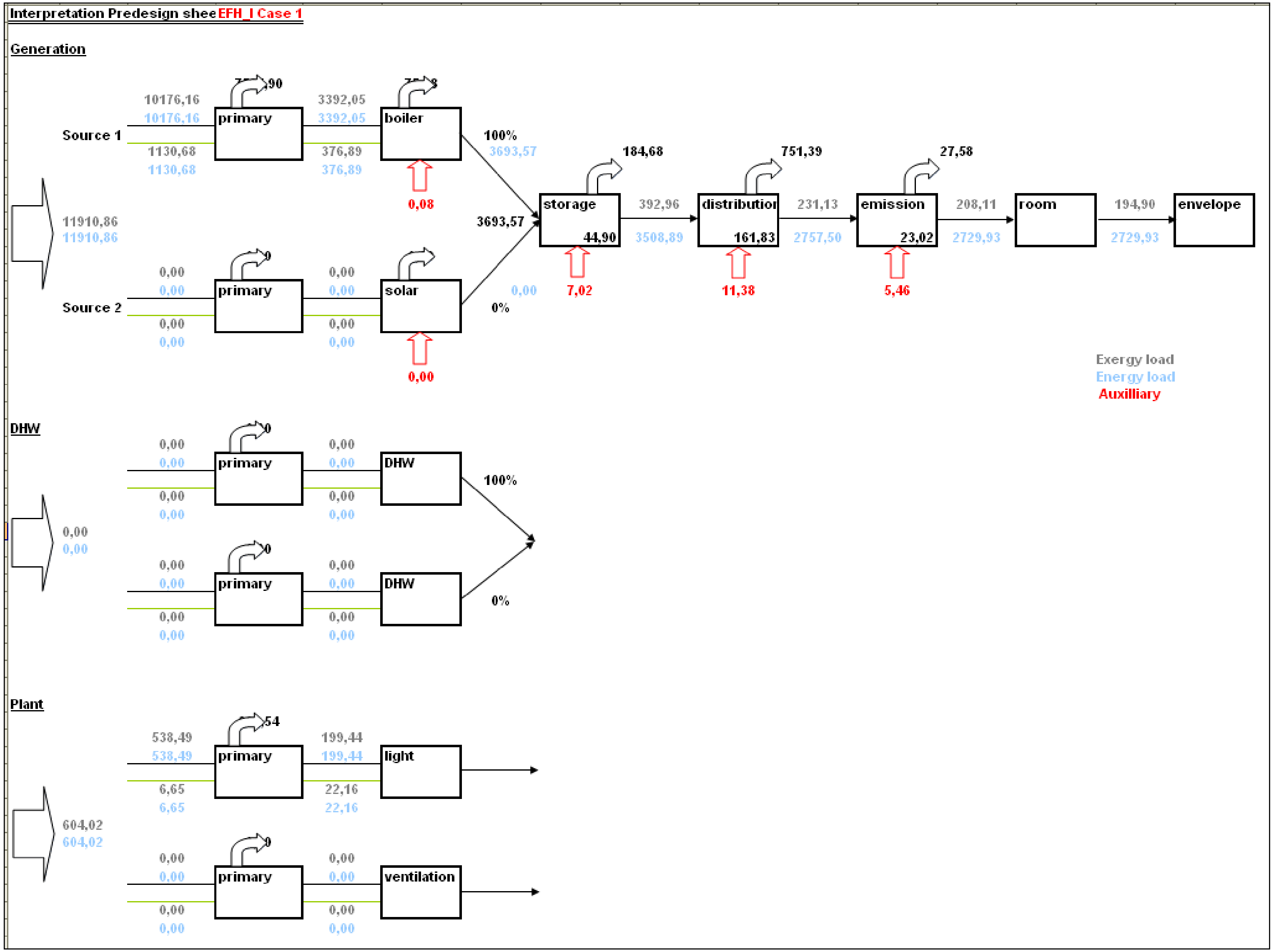

Figure 2: the modification of the model above was carried out by breaking down the energy flows in the generation and primary energy transformation subsystems in a fossil and renewable part.

The energy flows in the generation and primary energy transformation steps have been subdivided in their respective fossil and renewable shares. As a result, an exact determination of the pure-renewable share is possible – an aspect is not assessed in the EnEV calculation. Another advantage of this structure is the separate examination of the domestic hot water production, because this improves the clearness of the whole system.

Following is a brief description of the subsystems in the energy supply chain:

1. Primary energy transformation

Energy carriers found in nature are regarded as primary energy. In order to be exploited, these energy carriers have to be transported and transformed into a form usable for the building. Note that this transformation and transport of energy carriers requires additional energy. All these processes are considered within this first section.

It is possible to take the climatic aspect of the energy usage (like CO_2 emissions) into consideration within this analysis because the sources of renewable and fossil energies are dealt with separately. This is important for the power generation and distribution since high losses arise there.

2. Generation

The energy enters the building envelope as final energy. The energy carrier (e.g. oil, natural gas or electricity) has to be transformed into heat to warm up the rooms. This is normally carried out via a burning process in a boiler. For this process the heat generator usually needs additional energy (electricity), for instance to operate pumps and fans. Moreover, heat losses emerge.

3. Storage

Often, the facility planning includes a heat storage system. The losses within the storage system have to be considered. If required, needs for additional energy for recirculation have to be considered as well.

4. Distribution

The heat which is supplied by the heat generator and potentially saved in the storage system has to be transported to the emission system via a distribution system. Therefore, pipes are placed in walls and ceilings towards the distribution system. Heat losses appear according to the insulating standards for pipes. Additional energy might be necessary for the heat circulation and control equipment.

5. Emission:

Typical emission systems are radiators or floor heating systems, which transfer the heat to the room. Heat losses can appear depending on the system design. Additional auxiliary energy for the recirculation of the heating fluid is required.

6. Room air

Heat is exchanged from the surface of the emission system to the room. At this point no heat losses occur. However, the exergy content of the transferred energy changes based on the change of the temperature between the surface temperature of the heating system and that of the room indoor air. Subsequently, exergy losses arise.

7. Building envelope

All heat flows leave the building through its envelope as transmission and ventilation heat losses. Within this sub-system the net heat demand of the building, i.e. net energy losses in the building as energy system, are analysed. Exergy losses arise due to the different temperature levels between indoor air and outdoor ambient air conditions.

In figure 3 a screenshot of the menu for required input data to define the building and the drop-down menus for selecting building services are shown for illustration.

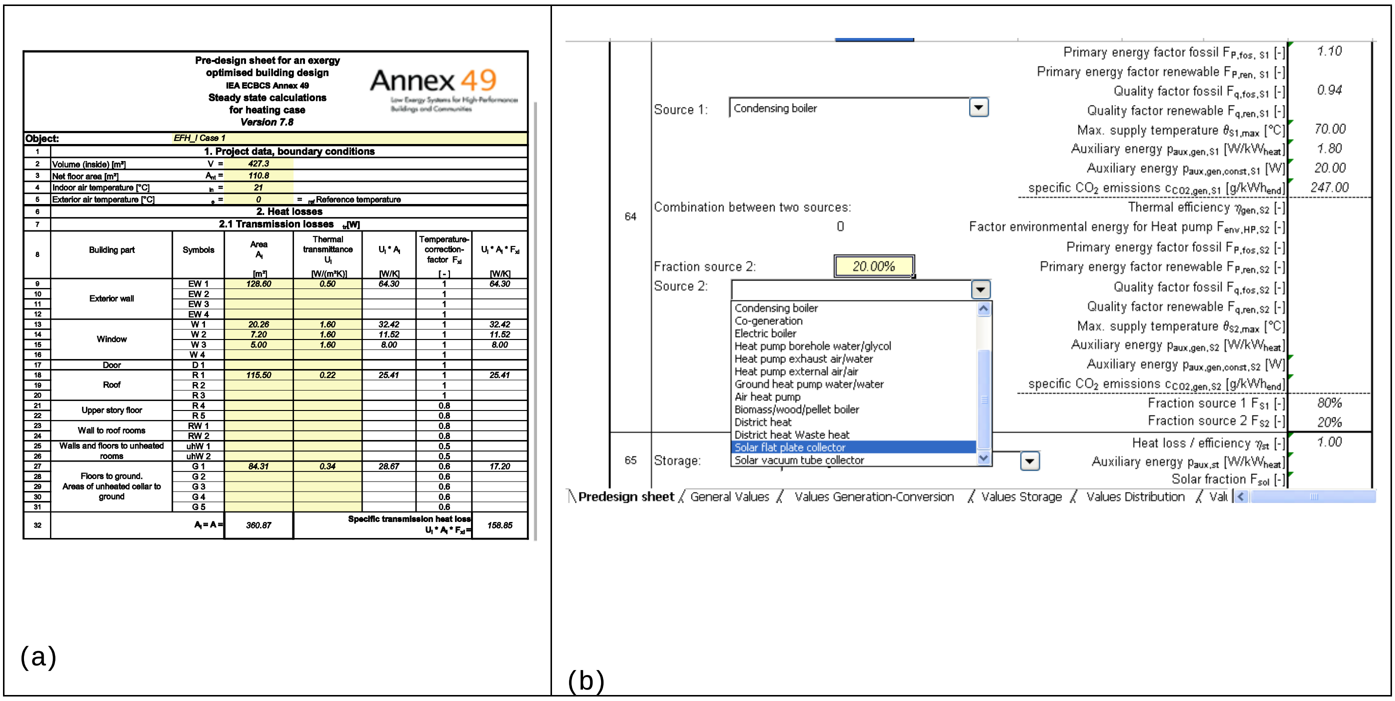

Figure 3: fields for input data to define the building envelope in the pre-design Excel tool (a) and drop-down menus for selecting building services (b).

Based on the obtained energy flows and depending on the chosen temperature levels for the building systems, an estimation of the exergy flows is carried out on a steady-state basis. The equations for each of the performed exergy calculations are directly shown in the calculation sheet. Furthermore, all required assumptions such as energy efficiencies and temperature levels regarded for the operation of the building systems are introduced in tables displayed in worksheets within the Excel file and referred to in the calculations. The user can modify the default assumed values for these parameters, allowing him to adjust the parameters to his particular system. This creates transparency and enhances understanding of the thermodynamic background and calculations within the tool.

The tool is divided into the following 10 table sheets containing corresponding data for each subsystem presented above (see figure 1):

Predesign sheet:	Input sheet for building and system parameters
	Energy and exergy analysis
	Evaluation of the calculation in graphs
General Values:	Configuration of all calculated values of the pre-design sheet
	Balancing of energy and exergy
Values Generation-Conversion:	Necessary system parameters to calculate the heat losses of the generation
	[Primary energy factors, quality factors, design temperatures, auxiliary energy, system effort number]
Values Storage:	Necessary system parameters to calculate the storage losses
	[Efficiency, auxiliary energy, solar fraction]
Values Distribution:	Necessary system parameters to calculate the distribution losses
	[Efficiency, temperature difference, design temperature]
Values Emission:	Necessary system parameters to calculate the emission
	[Supply and return temperature, auxiliary energy, max. heat emission]
Values DHW:	Necessary system parameters to calculate the power requirement for the hot water heating system
	[Input and supply temperature, flow, efficiency, primary energy factor, quality factor]
Interpretation:	Classification of the calculation results from generation until building envelope

Efficiencies:	List of parameters for characterising the energy and exergy performance of the studied object
Factors:	Summary list with the main factors chosen or assumed for the calculation of the studied object

2.2.3 Results

In the energy and exergy analyses all steps of the energy chain – from the primary energy source to the building and the environment (i.e. the ambient climate) are considered, following the energy chain as shown in Figure 1.

The calculated energy and exergy flows are illustrated in two diagrams. Here, a separation occurs for the heating system and the domestic hot water (DHW) production. Therefore, an energy and exergy analysis for each specific energy demand is possible (see figure 4).

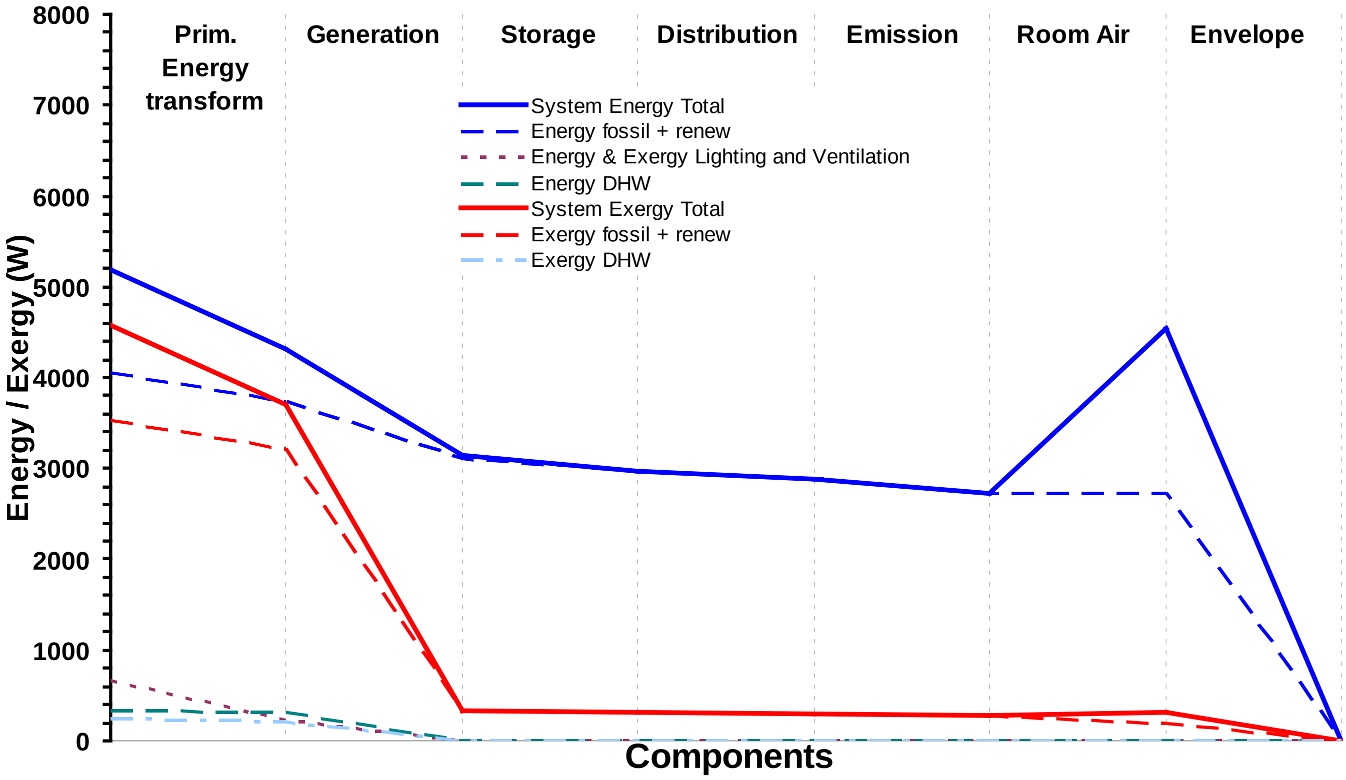

Figure 4: exergy and energy flows in each subsystem of the energy supply chain

Additionally, several parameters allow a direct and quantitative comparison between the performance of different building systems. The main parameters included for this use are:

- **overall exergy efficiency**: indicates the efficiency of the total energy supply chain of the building;
- **effort figures:** represent the amount of exergy losses arising in the supply chain;
- **exergy expenditure figures**: provide an idea of the “matching” between the quality levels of the energy demanded and supplied;

In figure 5 all energy and exergy losses are shown separately for each subsystem. Negative values of the energy and exergy losses in a component indicate gains in this component, e.g. solar gains. Since all energy flows are regarded in the balance (i.e. fossil and renewable), the only system where energy and exergy gains are possible is the building envelope. Here, energy gains through the building envelope contribute to compensating the total transmission and ventilation losses.

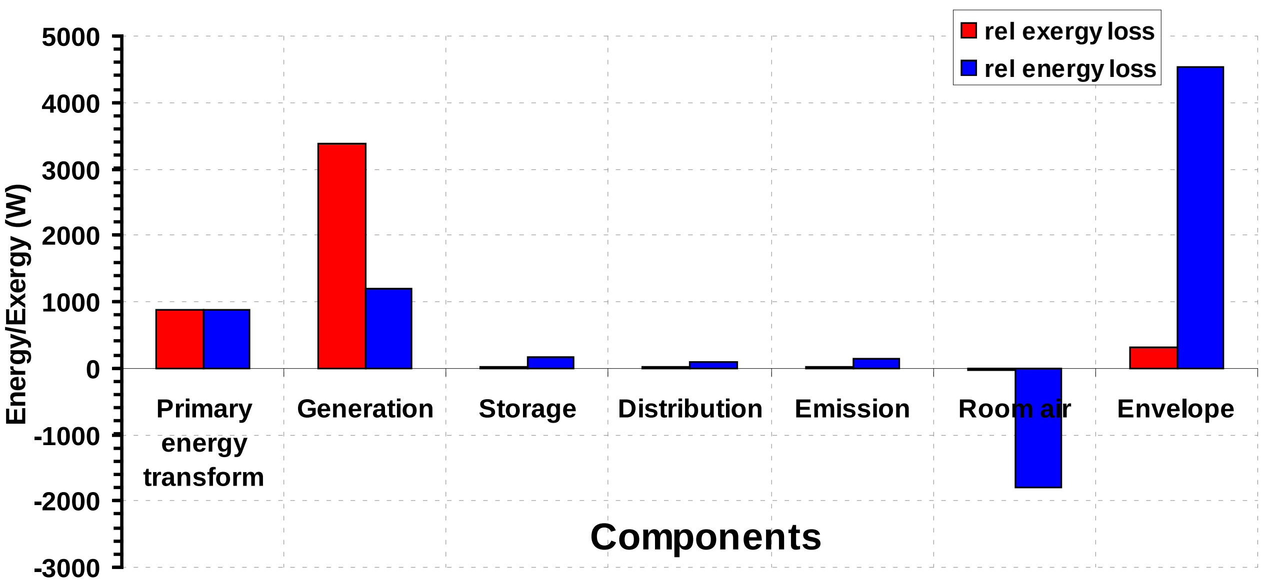

Figure 5: exergy and energy losses in each subsystem of the energy supply chain

Crosschecks

The Excel-tool is configured to review the consistency of the system. Three tests are used:

1. If the calculated heat demand Φ_H is higher than the possible maximum heat emission of the system $p_{heat,max}A_{nt}$, a warning message will be shown. $p_{heat,max}$ is the maximum heat emission/m^2 emission area and A_{nt}, is the total emission area available. New and modern buildings with advanced emission systems, such as thermal active building components require an adequate building envelope because of their limited maximum heating power. Following, a heating system with a higher possible heat emission should be used or the heating load should be reduced, e.g. through upgrading the standard insulation or inserting an aligned ventilation system with heat recovery. If the following condition is fulfilled the below-mentioned error message will be announced:

$$\frac{\Phi_H}{1{,}5} > p_{heat,\max} \cdot A_{nt}$$

"WARNING: Heating power demand is higher than the installed power! The system solution is NOT sufficient! Improve building envelope or use a more powerful system."

2. To check whether the diverse components of the heating system are chosen carefully and exactly, the temperature steps are compared with each other. The maximum supply temperature of the boiler $\theta_{s,max}$ has to be higher than the necessary inlet temperature of the emission system θ_{in}. If the following condition is fulfilled the below-mentioned error message will be announced:

   $$\theta_{S,\max} < \theta_{in}$$

   "WARNING: Error in system design. Needed inlet temperature NOT supplied by generation. Change system design."

3. The tool is only developed to calculate the heating cases. If the heating demand is negative the below-mentioned error message will be shown:

   $$\Phi_h < 0$$

   "WARNING: Overheating, cooling needed. Apply solar protection, reduce internal loads!"

   Moreover, a further remark or warning has been incorporated. As soon as a flat plate collector and tube collector respectively is used, this message appears:

   "PRIMARY ENERGY COMES FROM A RENEWABLE SOURCE - energy output from collector represented as primary energy/exergy"

The following two diagrams show the energy and exergy supply compared to the energy and exergy demand. The energy and exergy supplied must be equal to the energy or exergy demands plus all the losses within the supply processes.

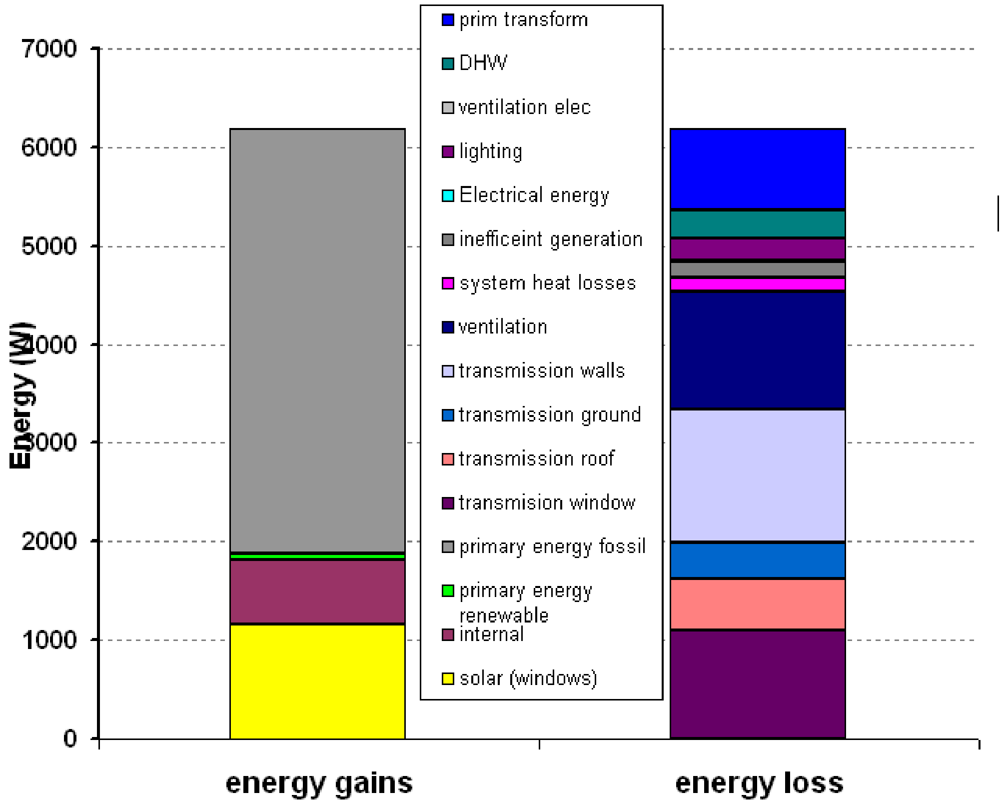

Figure 6: energy gains and losses

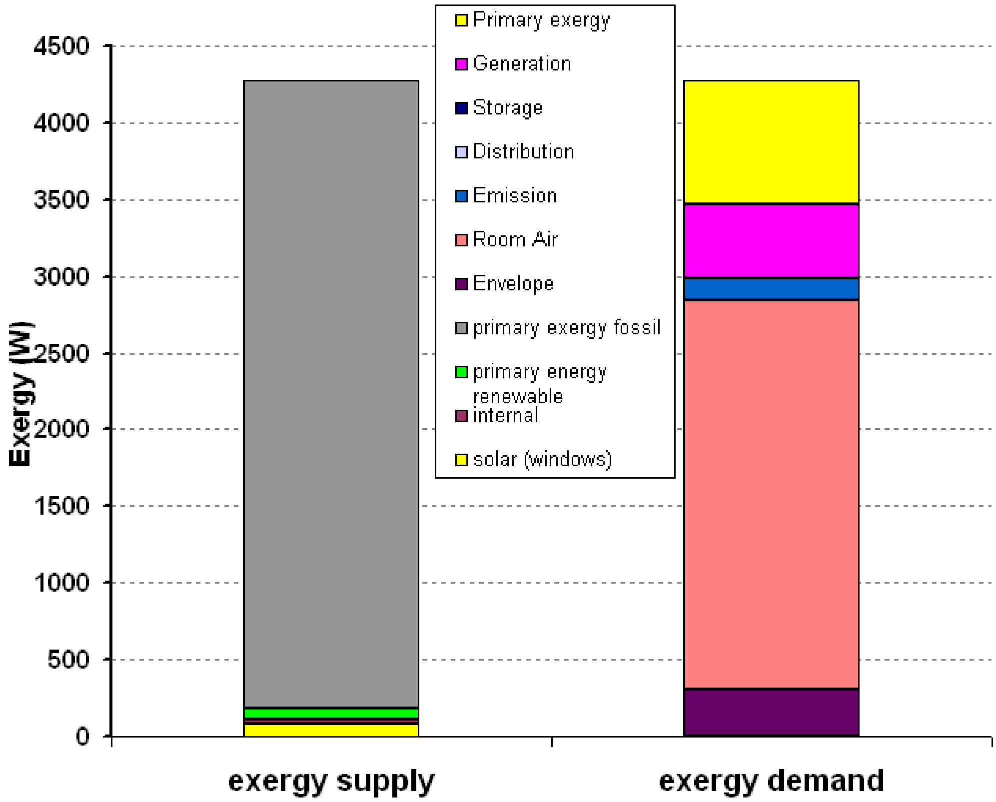

Figure 7: exergy supply and demand

2.2.4 Conclusions

The predesign tool enables calculating the energy and exergy flows in the supply chain for space heating and DHW supply of several building systems (e.g. boilers, heat pumps, solar collectors). Energy and exergy losses in each component of the supply chain can be identified, making it easy to spot the systems with greatest improvement potential.

The employed calculation method is similar to energy balancing calculations in German regulations, making the tool easier to understand. Furthermore, all equations are explicitly stated in the Excel sheet, ensuring transparency and allowing the user to follow all calculations steps easily. The tool is, thus, a perfect calculation tool for building planners, architects and building decision makers. It allows recognizing the impact of different choices (e.g. different building systems, different insulation level, etc.) in the energy and exergy performance and efficiency of supply.

Acknowledgement

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2.3 Benchmarking of low "exergy" buildings

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2.3.1 Introduction

Despite the efforts made to improve energy efficiency of buildings, the issue of gaining insight from an overall assessment and the comparison of different energy sources to improve this efficiency still exists (Dena, 2007; Schmidt and Shukuya, 2003). Today's analysis and optimisation methods do not distinguish between different qualities of energy flows during the analysis, although the building codes of a number of countries require assessing energy flows from different sources and weighing them against the primary energy factors. The primary energy factors necessary for the calculation are based neither on analytical ground nor on thermodynamic process analyses, yet they have been derived from statistical material and political discussion.

The exergy content expresses the quality of an energy source or flow. This concept can be used to combine and compare all flows of energy according to their quantity and quality (Rant, 1956; Rant, 1965, Schmidt, 2001). Buildings still account for more than one third of the world's primary energy demand (Schmidt, 2001) and most of the energy is used to maintain room temperatures of around 20°C. In this sense, because of the low temperature level, the exergy demand for applications in room conditioning is naturally low. In most cases, however, this demand is satisfied with high quality sources, such as fossil fuels or with electricity (Schmidt, 2004).

2.3.2 The Exergy and primary energy approach to the analysis

Energy use assessment in buildings is normally based on quantitative considerations alone. By weighing different energy sources against primary energy factors, some aspects of a more qualitative assessment can be considered. Yet, in principle, the design of energy supply structures is founded on meeting quantity-based energy demand in buildings. With the so-called LowEx approach, a step further is to be taken. Not only are quantities of energy demand and supply considered, but the quality of energy is also included (Jóhannesson and Schmidt, 2001; Ala-Juusela, 2004; Keller, 2007; Schmidt and Shukuya, 2005).

In Germany, the typical primary energy efficiency for heating of newly erected dwellings, equipped with good building service systems, is about 70%. If exergy is considered, the picture changes. The exergy efficiency of the heating process is only about 10%. This section discusses the question of how an exergy analysis could help to increase efficient energy use.

An exergy analysis starts with the definition of boundary conditions and the estimation of the exergy demand of the occupied zones. A typical outdoor ambient air temperature in winter can be considered as 0°C in central/northern Europe, which is also the reference temperature for the exergy analysis. With an indoor air temperature of 21°C within the heated spaces, the exergy factor of the heating energy turns out to be 7% (item 2.1.4 discusses the exergy factor, also known as the quality factor). The quality factor is derived from the Carnot efficiency, and depends on the temperatures inside the room and in the ambient environment. Even in more extreme weather conditions, the exergy factor will not exceed 15%. Similar considerations can be made for summer and cooling conditions, but are not the subject of this section. Summer conditions are addressed in section 2.4 of this book, from the perspective of a dynamic exergy analysis.

2.3.3 A Case Study

For the following considerations, a building from the IWU study (IWU, 2003) – a single-family dwelling, built between 1995 and 2000 – has been chosen as an example. For this home, an indoor air temperature of 21°C is assumed as the reference temperature, and the ambient air temperature during a typical winter day is 0°C. The mean heat transmission coefficient of the building envelope $H'_{T,}$ a measure for the insulation standard of the building (mean U-Value), is 0.44 W/m²K. The building is to be ventilated via windows and natural forces, and a mean air exchange rate of 0.6 ACH is assumed. The preparation of the required domestic hot water is done via direct electrical heating elements and assumed to be 45 l/(pers*d) with about 2.5 persons present as a mean value.

The calculation for this study has been conducted with the IEA Annex 49 analysis tool (Annex 49, 2008) - an Excel based spreadsheet tool for steady state calculations. The method is described in detail in and based on Schmidt (2004). The improved version of the tool is also described in section 2.2. The calculated figures are actual loads for typical conditions. The building properties and domestic hot water demand, as well as indoor and outdoor conditions, are taken as fixed parameters. For the building service equipment and the heating system of the building, six different variants have been studied:

1. A **condensing boiler** as the primary heat generator and standard radiators with the temperature levels for supply and return of **55/45°C** as the emission system.

2. A **condensing boiler** as the heat generator and a floor heating system with temperature levels for supply and return of **28/22°C**.

3. A **biomass-fired boiler** (e.g. wooden pellet burner) as the heat generator and a floor heating system with temperature levels for supply and return of **28/22°C** as the emission system.

4. A **condensing boiler** is assumed as the primary heat generator and the **solar thermal** system, covering 40% of the heating load, as the secondary heat source. Floor heating with temperature levels for supply and return of **28/22°C** as the emission system.

5. A **ground source heat pump** with a ground heat exchanger as the primary heat source and a floor heating systems with temperature levels for supply and return of **28/22°C** as the emission system.

6. The heat supply is covered by a **district heating** connection, which is fired with fossil or renewable sources. Also, for this variant, a floor heating systems with temperature levels for supply and return of **28/22°C** as the emission system.

2.3.4 Results

A common energetic assessment of the building under steady state conditions is shown in figure 1. Because the primary energy factors of the fuel sources are different, the fossil part of the energy supply varies between the analysed variants. The share of renewable energy also varies, but the total energy demand of the building remains the same in all cases. Only the efficiency of the chosen building service system may vary.

Considering the primary energy helps to identify saving measures for fossil energy sources and the related CO_2 emissions, but can hardly give any real indication about efficient energy use.

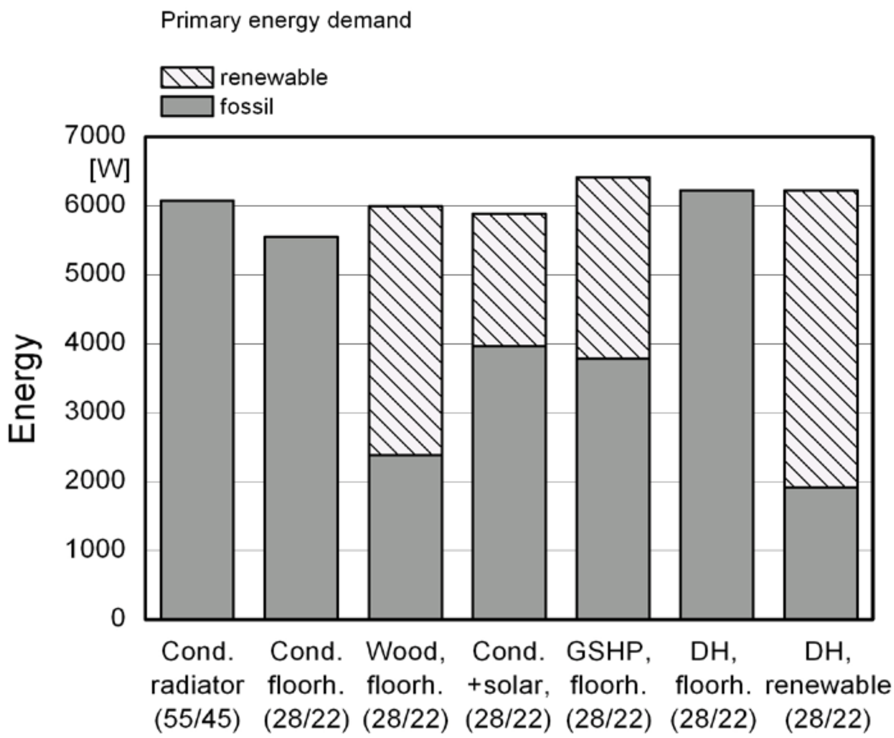

Figure 1: calculated primary energy demand (fossil and renewable) for the chosen variants of the building service equipment, steady state calculation

A comparison of an energetic and exergetic assessment of the primary energy demand from fossil and renewable sources is shown in figure 2. It can be clearly seen that the different building service system configurations entail a need for largely varying amounts of exergy to meet the heating demand. Especially the condensing boiler, where natural gas is used and burned, utilises about 100% exergy for that task. This is also true for the wooden pellet burner. Other systems are able to satisfy the requirements with less than half of the exergy. This is shown in the results from, for example, the systems operating with a district heating supply.

The exergetic assessment of these heating systems opens up the possibility to compare the performance (and the efficient use of different energy sources) in a thermodynamically consistent way. This basis is free from the influence of political discussions and national borders. The potential of renewable energy sources is also correctly taken into consideration. It can be concluded that a rational use of energy has to be assessed with an additional exergy analysis and that exergy use should be limited, as it is done today with primary energy. This has to happen under the consideration of the entire building as one system (Schmidt and Ala-Juusela, 2004; Schmidt, 2007).

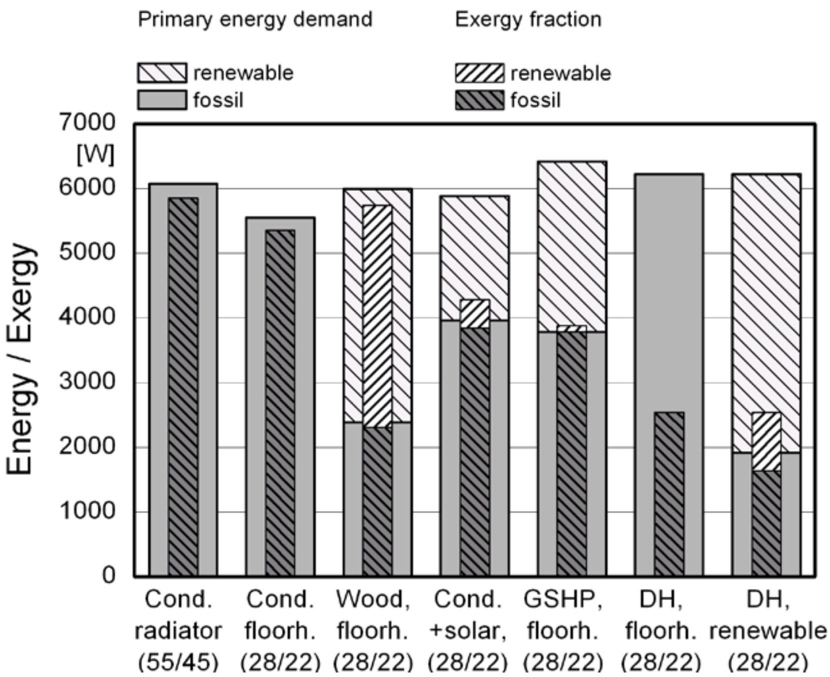

Figure 2: calculated primary energy demand (fossil and renewable) and the related exergy fractions (the exergy content of the primary energy demand) for the chosen variants of the building service equipment, steady state calculation

2.3.5 Introducing a new LowEx Benchmark: the exergy expenditure figure

To make the quantity exergy manageable for building designers and to present engineering-based orientation to make the choice between building service solutions, a new parameter is presented here. This parameter, the exergy expenditure figure ε, is the quotient of the exergetic effort (the total exergy input) of the system or system component considered and the energy use (the total energy input) of this system or system component. It is defined as:

$$\varepsilon = \frac{effort}{use} = \frac{\dot{E}x_{in} + \dot{E}x_{aux}}{\dot{E}n_{out}} \tag{1}$$

The exergy expenditure figure for an ideal case, ε_{ideal} could be defined as

$$\varepsilon_{ideal} = \frac{\dot{E}x_{Demand,Zone}}{\dot{E}n_{Supplied,Zone}} \tag{2}$$

since $\dot{E}x_{in} = \dot{E}x_{Demand,Zone}$ and $\dot{E}x_{aux} = 0$.

A component, e.g. a radiator, is designed to deliver a specified heating power to the room or space it is designed to heat. Energy is transmitted and used within the space, and heat is exchanged from the heat carrier (e.g. water) to the air within the room. A component should perform this task using the smallest possible amount of thermal exergy. The use of high quality (auxiliary) energy, e.g. electrical power, should also be low, as should losses to the environment.

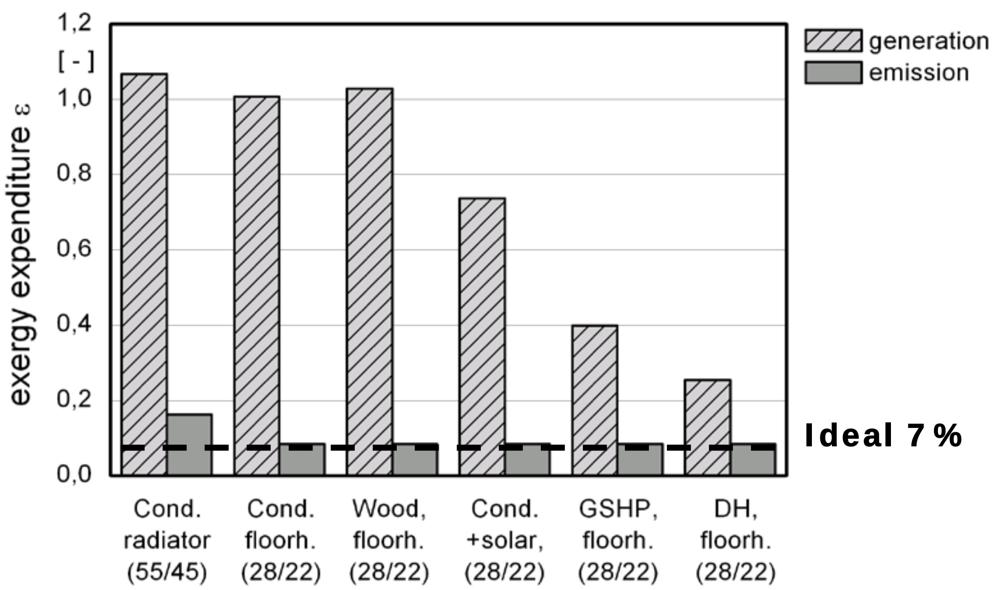

Figure 3: assessment of the components "heat generation" and "emission system" with the exergy expenditure figure for the chosen variants of the building service system.

As previously described, the ideal exergy expenditure of a zone is only 7% of the heating energy demand, derived from the exergy factor of the heat demand of the zone. This value is directly compared to the exergy expenditure figures of the different variants in Figure 3. It is shown that different heat generators satisfy the demand with a more or less well-adapted supply. Heat generators which utilise a combustion process use much more exergy than required, and are thus less “LowEx”. These differences can also be demonstrated for emission systems. The radiator system entails larger temperature differences and thus uses more thermal exergy than the floor heating system to heat the same room. The exergy expenditure of the floor heating system is close to ideal conditions, since this emission system operates very close to room temperature.

2.3.6 Proposed exergy-based classification

The exergy approach provides a thermodynamically consistent basis for comparison of different energy utilisation systems in buildings. Figure 2 shows the renewable and fossil parts of the exergy content of primary energy demand for the variants analysed. Figure 4 shows the sum of the fossil and renewable parts for the exergy content of primary energy demand. The figure illustrates a proposed classification into Limiting, LowEx and Ideal situations.

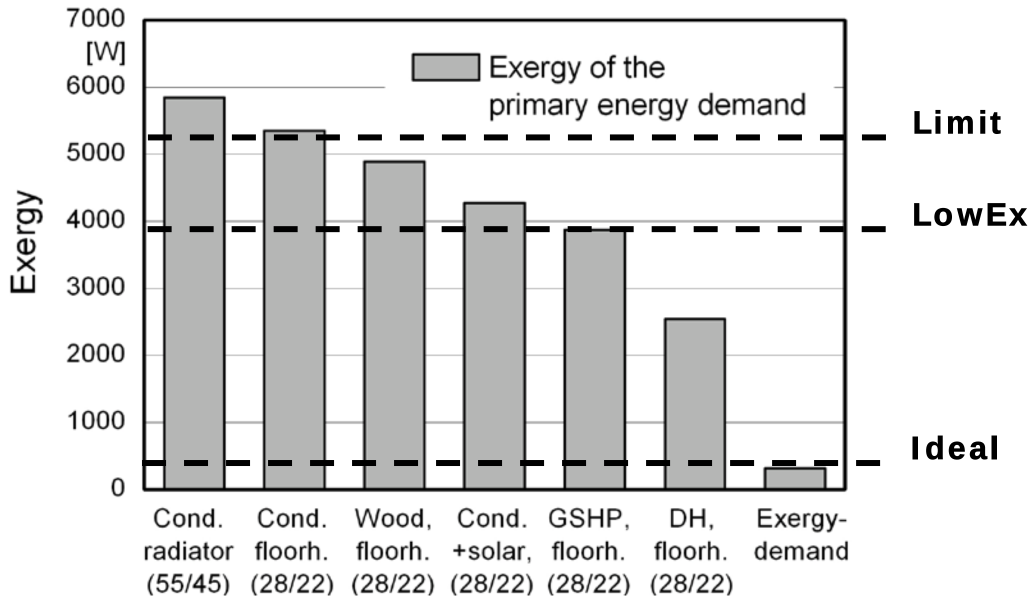

Figure 4: calculated exergy contents of total primary demand (fossil and renewable) for the chosen variants of the building service equipment (steady state) and a proposed classification.

An ideal line, or lower limit, can be drawn based on the minimal thermal exergy demand of the zone, based on equation (2). On the other hand, an upper limit of the exergy of the primary energy demand should be determined according to exergy of the thermal primary energy demand of the heat generation and emission systems with the least thermal exergy losses, assuming good building and building service equipment solutions, similar as those used for limiting fossil primary energy demands. For this particular case study, the exergy demands for the ground source heat pump and for the district heating systems are the lowest of the cases considered and are then defined as LowEx. The LowEx line corresponds to a good match between thermal exergy supply and demand, which results in limited exergy destruction in the heat generation and emission systems

2.3.7 Conclusions

The following three main design principles can be derived from the analysis in this section:

- the exergy demand of a zone should be met with a suitable supply system, i.e. the actual exergy expenditure figure should be as close as possible to the ideal exergy expenditure (which corresponds to the exergy demand of the zone);
- setting limits to primary energy demand is a useful means of reducing primary energy input and the related CO_2-emissions from buildings. This is already mandatory in a number of European countries (e.g. Germany). The exergy analysis discussed in this section reinforces the need for limiting primary energy demand. The additional requirement to reduce the maximal heat transmission losses, by setting upper limits to the mean transmission heat loss coefficient is a good means of securing a good building envelope construction that helps to reduce heating energy demand;
- to assess and better use the full thermodynamic potential of energy, it is important to curb the exergy demand of both fossil and renewable sources. This could be done by using already known procedures for limiting primary energy demand.

Acknowledgement

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Nomenclature

$\dot{E}n$	Energy rate [W]
$\dot{E}x$	Exergy rate [W]

Greek letters

ε	Exergy expenditure [-]

Subscripts

aux	auxiliary
Demand,zone	Demand of the zone
in	input
out	output
Supplied,zone	Supplied to the zone

2.4 Steady versus dynamic exergy analysis of heating and cooling systems

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2.4.1 Introduction

It is well known that dynamic energy analyses of buildings and of heating and cooling systems are much more reliable than steady state ones. Therefore, the steady state approach is usually adopted only for first estimations of the energy demand/supply or for calculating the peak loads. In turn dynamic exergy analyses in the built environment are uncommon. A few examples can be found in literature, where a time varying outdoor temperature is adopted for the reference environment (Asada and Shukuya 1997, 1999; Asada and Takeda 2002; Asada and Boelman 2004; Alpuche et al. 2005). However it may be argued that in this case exergy flows and then exergy indicators could be significantly time dependent, since temperature levels in building systems are very close to the reference temperature.

Clearly more effort is needed to carry out a dynamic analysis, therefore the question arises on how different can be the results of a dynamic exergy analysis compared to a simple steady state one. If a significant difference is found, it is worth investigating how this is affected by the climatic context and by the kind of heating/cooling system.

Therefore in this research both steady and dynamic approach are applied to evaluate the exergy performance of some heating and cooling systems in two representative Italian climates. The results of the two approaches are then compared and discussed.

2.4.2 Methodology

The case study chosen regards a typical residential unit, located either in Milan (Northern Italy) or in Palermo (Southern Italy). Two different heating and cooling systems are alternatively coupled to the building, namely a reversible air source heat pump (ASHP) used both in winter and in summer, and a condensing gas boiler (CB) for winter heating with a direct ground cooling system (DGC) for summer cooling. While the energy efficiency of the ASHP[7] and of the CB is assumed to vary with outdoor temperature, as shown in Figure 1 for

[7] COP data for the ASHP are taken from the example file of type 655 model in Trnsys library

the winter case, a constant COP = 10 is assumed for the DGC. A more detailed description of the building and the systems can be found in (Angelotti, Caputo 2007).

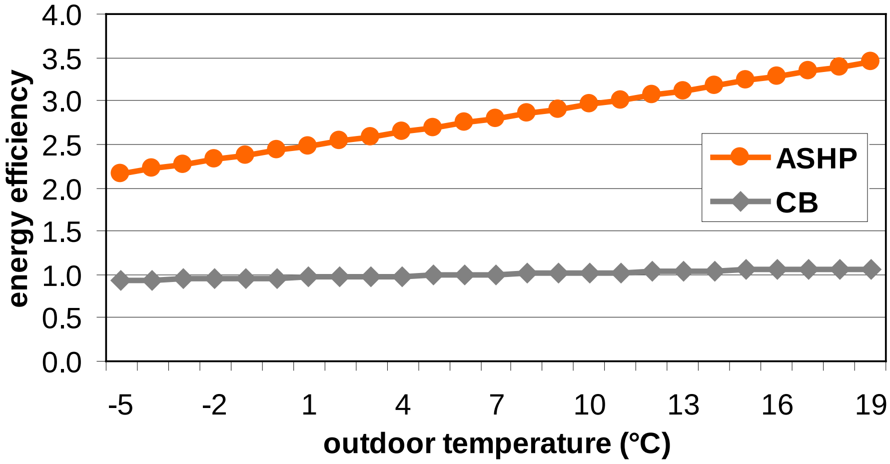

Figure 1: full load energy efficiency of the ASHP (COP) and of the CB versus the outdoor temperature

The exergy performance of the systems coupled to the building is assessed through the exergy efficiency, defined as in equation (1):

$$\Psi = \frac{Ex_{deliv}}{Ex_{in}} \tag{1}$$

Ex_{deliv} is the exergy of heat or cold Q delivered to the building i.e.:

$$Ex_{deliv} = Q\left|1 - \frac{T_0}{T_r}\right| \tag{2}$$

where T_r is the building indoor temperature and T_0 the reference temperature, assumed equal to the outdoor air temperature. Ex_{in} is the exergy input by the system, that depends on the boundary chosen for the analysis. If the boundary is set at the building and system level, the exergy input is the exergy of the spent fuel in the case of the CB and the electricity input in the cases of the ASHP and the DGC. Including the primary energy conversion step, in the cases of the ASHP and of the DGC the exergy consumed is the exergy lost in a typical Italian power plant to produce the electricity input of the building systems. In this regard the present national electricity energy conversion efficiency η_{el} = 0.41 has been considered.

Steady state approaches

Considering a steady state approach, the reference temperature can be chosen as a design condition, like the ones that are usually adopted for sizing HVAC, or as a mean value over a given period (a month, a season, a year). With the ambition to possibly highlight a steady state approach leading to minimum discrepancy with the dynamic, two steady state approaches are considered:

- "steady design approach", i.e. setting T_0 equal to the design temperatures for the two climates $T_{0,des}$ (in Milan -5°C in winter and 32°C in summer, in Palermo 5°C in winter and 32°C in summer);

- "steady mean approach", i.e. setting T_0 equal to the monthly mean or the seasonal mean temperatures for the two climates $T_{0,mean}$.

Therefore, following the general definition in equation (1), two steady state exergy efficiencies can be found. In the case of the ASHP, setting for example the boundary at the system and building level, using equation (2), considering that Ex_{cons}=W and that COP=Q/W, they become:

$$\Psi_{stea,des} = COP(T_{0,des}) \cdot \left(1 - \frac{T_{0,des}}{T_r}\right) \tag{3}$$

$$\Psi_{stea,mean} = COP(T_{0,mean}) \cdot \left(1 - \frac{T_{0,mean}}{T_r}\right) \tag{4}$$

In both equations T_r is set equal to the desired indoor temperature (20°C in winter and 26°C in summer). Therefore the exergy efficiency is related to the energy efficiency or COP and to the Carnot factor of the delivered heat/cold, both depending on the outdoor temperature. Similar expressions can be derived for the CB and for the DGC.

Dynamic approach

In this case a dynamic energy analysis of the building and systems behaviour is performed using the software TRNSYS 16 with a time step of one hour[8]. Therefore the system exergy efficiency may be evaluated at every time t_k, from the corresponding exergy flows. In the case of the ASHP, again setting the boundary at the building level, it is simply:

[8] Meteonorm weather files for Milano and Palermo are used

$$\Psi\left(t_k\right) = COP\left(t_k\right)\left(1 - \frac{T_0(t_k)}{T_r(t_k)}\right) \tag{5}$$

and a monthly or seasonal mean exergy efficiency $\left\langle \Psi_{dyn} \right\rangle$ may then be calculated as an average value over the chosen period, as in equation (6):

$$\left\langle \Psi_{dyn} \right\rangle = \frac{1}{m}\sum_{k=1}^{m}\Psi(t_k) \tag{6}$$

When evaluating the seasonal average, the heating season defined by law in Italy is adopted, that is from October 15th to April 15th in Milano and from December 1st to March 31st in Palermo. As the cooling season is not set by law, in this work it is simply considered as the complementary period.

Moreover, in order to better characterise the dispersion of the distribution of $\Psi(t_k)$, a standard deviation σ is also calculated.

2.4.3 Results

The comparison between the different exergy performance calculation approaches is carried out in the following two steps: first of all the steady and the dynamic exergy efficiencies are compared in the two climates in the case of the ASHP, taking the boundary at the system and building level (Angelotti, Caputo, 2009); then, limiting to some representative months of the heating and cooling seasons, the steady and the dynamic exergy efficiencies of the ASHP, the CB and the DGC are considered, discussing whether the calculation methodology might affect a ranking among different systems based on exergy performance. In this case the primary energy conversion step is included.

Steady vs dynamic exergy efficiency of the ASHP

The results of the steady design calculation and of the seasonal dynamic calculation in the case of the ASHP are reported in Table 1 for the two reference climates. Regarding the dynamic evaluation, both the seasonal dynamic efficiency Ψ_{dyn} and the standard deviation of the hourly data σ are reported. It may be noticed that in general in the cooling season σ is in the same order of magnitude as Ψ_{dyn}, meaning that the dynamic is quite important.

The discrepancy between the two approaches is evaluated in terms of the relative difference of the results, calculated taking the dynamic results as references. Besides the exergy efficiency figures, the table reports also the COP and the Carnot factor figures. Looking at Table 1 a general remark can be made: exergy performance results differ from energy performance results, because of the dependency from the Carnot factor. Quite often the discrepancy dynamic vs steady in the COP and in the Carnot factor have opposite sign (see for example the case of Milano heating: the dynamic COP is 17% greater than the steady design COP, while the dynamic Carnot factor is 37% smaller than the steady design Carnot factor). In the end the sign in the discrepancy in the exergy efficiency is determined by the Carnot factor. Then, at least for the considered ASHP, the dynamic effects of the Carnot factor dominate those of the COP.

Table 1 shows that the differences between the two approaches are more important in the summer period than in the winter period for both sites. The cooling season relative differences are quite large and could hardly be considered acceptable. Both in winter and in summer, the differences tend to be larger for the warmer climate of Palermo than for Milano. Both results may be explained noticing that any time the ratio T_0/T_r is large (i.e. in general in summer, but also in winter for warmer climates) the Carnot factor and the exergy efficiency are very sensitive to the reference temperature and to its dynamic behaviour.

	Milano		**Palermo**	
	Heating	**Cooling**	**Heating**	**Cooling**
$T_{0,des}$ (°C)	-5	32	5	32
$COP_{stea,des}$	2.25	2.15	2.81	2.15
COP_{dyn}	2.71	2.82	3.17	2.89
COP relative difference [%]	**17**	**24**	**11**	**26**
$1- T_{0,des} / T_{r,des}$	0.081	0.020	0.047	0.020
$\|1-T_0(t) / T_r(t)\|$	0.059	0.007	0.033	0.006
Carnot factor relative difference [%]	**-37**	**-202**	**-40**	**-256**
$\Psi_{stea,des}$	0.181	0.043	0.132	0.043
Ψ_{dyn}	0.157	0.017	0.100	0.014
σ	0.02	0.01	0.02	0.01
Exergy efficiency relative difference [%]	**-16**	**-152**	**-31**	**-217**

Table 1: Steady state evaluation based on design temperatures compared with seasonal dynamic evaluation for the ASHP

Tables 2 and 3 report the comparison between the steady mean approach and the dynamic, respectively for Milano and Palermo. The steady mean approach could be applied only to the heating cases, because the monthly mean values of the outdoor temperatures during summer in both climates are lower than the indoor desired temperature, leading to nonsense.

Month	Jan	Feb	Mar	Apr	Oct	Nov	Dec	Heating season
$<T_0>$ (°C)	1.6	3.2	7.2	11.7	10.6	5.9	2.1	4.5
$COP_{stea,mean}$	2.62	2.71	2.93	3.19	3.13	2.86	2.65	2.8
COP_{dyn}	2.65	2.68	2.79	2.91	2.73	2.82	2.68	2.7
COP rel. difference [%]	**1**	**-1**	**-5**	**-9**	**-14**	**-1**	**1**	**-3**
$1-<T_0>/T_r$	0.058	0.053	0.039	0.024	0.027	0.044	0.057	0.049
$<1-T_0(t)/T_r(t)>$	0.062	0.061	0.055	0.047	0.058	0.053	0.061	0.059
Carnot factor rel. difference [%]	**7**	**13**	**29**	**50**	**53**	**17**	**7**	**18**
$\Psi_{stea,mean}$	0.153	0.144	0.115	0.076	0.086	0.125	0.150	0.135
Ψ_{dyn}	0.162	0.160	0.149	0.136	0.157	0.145	0.159	0.157
σ	0.01	0.02	0.02	0.02	0.01	0.02	0.02	0.02
Exergy efficiency rel. difference [%]	**9**	**10**	**23**	**44**	**45**	**14**	**6**	**14**

Table 2: Comparison between steady state evaluation based on monthly mean temperatures and dynamic evaluation for Milano

The exergy efficiency discrepancies reported in Tables 2 and 3 are in the same order of magnitude as those in Table 1, meaning that adopting mean values rather than design values for the reference temperature in a steady state approach does not lead in general to a better matching with dynamic approach.

Month	**Jan**	**Feb**	**Dec**	**Heating season**
$<T_0>$ (°C)	12.8	13.0	14.1	13.4
$COP_{stea,mean}$	3.25	3.26	3.32	3.28
COP_{dyn}	3.15	3.11	3.25	3.17
COP rel. difference [%]	**-3**	**-5**	**-2**	**-4**
$1-<T_0>/T_r$	0.020	0.020	0.016	0.018
$<1-T_0(t)/T_r(t)>$	0.035	0.037	0.028	0.033
Carnot factor rel. difference [%]	**42**	**47**	**45**	**46**
$\Psi_{stea,mean}$	0.065	0.064	0.052	0.059
Ψ_{dyn}	0.102	0.110	0.088	0.100
σ	0.02	0.02	0.02	0.02
Exergy efficiency rel. difference [%]	**36**	**42**	**41**	**41**

Table 3: Comparison between steady state evaluation based on monthly mean temperatures and dynamic evaluation for Palermo

In turn on a monthly basis we may notice that the relative differences vary significantly. For instance in Milan (Table 2) they vary from a minimum of 6% in December to a maximum of 45% in October. This outcome is clearly explained in Figure 2, where the monthly relative difference in the exergy efficiency is plotted against the fraction of the time in a month in which the ASHP is on. The less the ASHP is on, the less the monthly mean temperature is representative of the ASHP operating conditions and then the larger is the discrepancy between a steady state evaluation based on the outdoor monthly mean temperature and a dynamic one, taking into consideration only those outdoor temperatures when the ASHP is switched on.

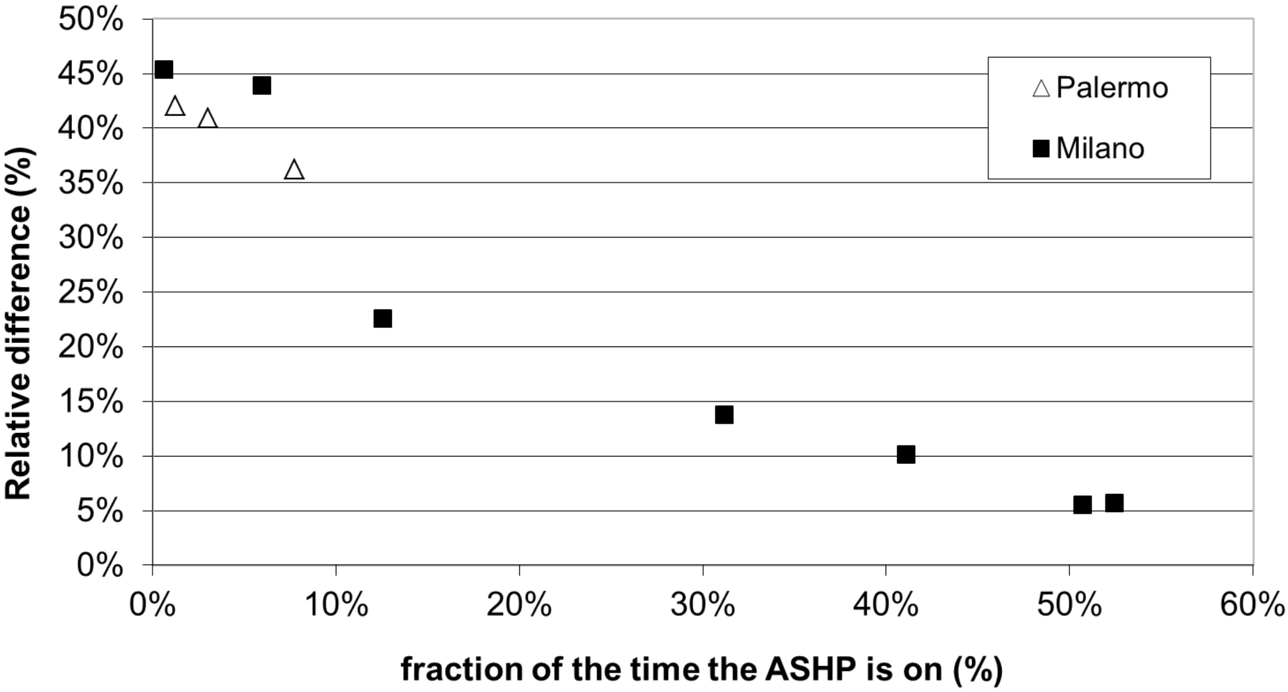

Figure 2: Relative difference between steady state analysis based on monthly mean temperatures and the dynamic one, vs the fraction of the time that the ASHP is on

Comparing different systems on a steady vs dynamic basis

Considering for simplicity only January and July, the steady design, steady mean and dynamic exergy efficiencies of the ASHP, the CB and the DGC are reported for comparison in Table 4. Data for the CB and the DGC are based on (Angelotti, Caputo 2007). Since the aim is to compare the systems on the basis of their exergy efficiency, the primary energy conversion step is included. Therefore the figures shown refer to the primary exergy efficiency.

According to the results shown in Table 4, the primary exergy efficiencies of the ASHP and the CB are similar. Therefore, it happens that, depending on the methodology adopted, the exergy performance of the ASHP is higher or, on the contrary, the performance of the CB is higher. For instance in Milano, the CB has a better performance according to a steady design approach, while the ASHP has a better performance according to a steady mean and a dynamic approach. In Palermo, the exergy efficiency of the CB is higher following the steady mean approach, while it is lower following the steady design and the dynamic one.

At the same time, since the ASHP and the DGC primary exergy performances are sufficiently far apart, their comparison is not affected by the methodology adopted to derive the exergy performance.

		Milano		Palermo	
		January	July	January	July
$\Psi_{stea,des}$	**ASHP [%]**	7.5	1.8	5.4	1.8
	CB [%]	7.9	-	5.1	-
	DGC [%]	-	8.2	-	8.2
$\Psi_{stea,mean}$	**ASHP [%]**	6.3	-	2.7	-
	CB [%]	6.1	-	2.9	-
	DGC [%]	-	-	-	-
Ψ_{dyn}	**ASHP [%]**	6.6	0.7	4.2	0.6
	CB [%]	6.2	-	3.3	-
	DGC [%]	-	4.8	-	3.2

Table 4: Comparison among the primary exergy efficiencies of the different heating/cooling systems according to the different methodologies

2.4.4 Conclusions

Despite the fact that a dynamic approach could be time consuming and complex, this analysis demonstrates the importance of adopting it if one of the following conditions occurs:

- the cooling season is considered;
- in the given month or season the climate is mild, so that the system is expected to work for a small fraction of the time, and thus the average outdoor temperature over the period is not representative of the actual operating conditions.

In the remaining situations, such as for heating evaluations in cold climates, discrepancies between dynamic and steady state evaluations are significant but not dramatic. It should be kept in mind that, if the purpose of the exergy analysis is to compare different alternative systems for heating or cooling, the choice of the kind of methodology, steady or dynamic, may influence the ranking when systems with similar performances are compared, such as the ASHP and the CB considered in this section.

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Nomenclature

ASHP	Air Source Heat Pump
CB	Condensing Boiler
COP	Coefficient of Performance [-]
DCG	Direct Ground Cooling [-]
Ex	Exergy [J]
m	Number of time steps [-]
Q	Heat [J]
T	Temperature [K]
t	Time [s]
< >	average

Greek letters

η	Energy efficiency [-]
σ	Standard deviation of the exergy efficiencies at different time steps [-]
Ψ	Exergy efficiency [-]

Subscripts

deliv	delivered
des	design
dyn	dynamic
el	electric
in	input
mean	mean

r	room
stea	steady
0	reference

CHAPTER 3
EXERGY AS A SUSTAINABILITY INDICATOR

Introduction

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Exergy is most of the times thought of as energy. Exergy is the available energy; it is the ability to produce work, whereas energy is the ability to produce motion, as noted by Wall in 1986. The term “exergy” was first used by Zoran Rant in 1953 and its origin is based on the Greek words ex (external) and ergos (work).

Exergy is based on the second law of thermodynamics, which has both economic and environmental significance.

Exergy is not conserved and it can be used as a common measure of resource quantity. It can be used to measure and compare resource inputs and outputs, and to take into consideration waste and losses. In this sense exergy can be used as a general resource concept. With the use of the exergy concept, inefficient and wasteful resource use will become obvious.

This, in turn, can lead to improvements and clarify the steps that must be taken. The exergy content of a natural resource input to the economy can be interpreted as one general measure of its potential “usefulness”. Natural resources can be considered as of two kinds: the resources based on natural flows such as solar energy, wind energy water etc., which are considered renewable resources, and the resources that are based on stocks. The dead stocks include oil, minerals, metals etc., while the live stocks include the forests, fields etc. An exergy-rich metal or mineral is more useful and more valuable than a stock containing less exergy. However, the unconditional use of exergy-rich material could lead to harmful consequences. The use of exergy-rich oil leads to emissions that have a major impact on climate change. On the other hand, the use of low-exergy flows will not lead to environmental impacts. The association of exergy with value and potential harmfulness suggests that exergy could be used as an indicator for the health of the environment and for the use of resources. Exergy can be used as a sustainability metric in the assessment of systems and processes.

Exergy analysis is a methodology that uses mass and energy conservation principles in combination with the second law of thermodynamics. The use of exergy analysis can lead to the more efficient use of resources, since it pinpoints the location of losses and wastes and determines their magnitude.

3.1 Exergy Indicators in the Building Environment

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3.1.1 Introduction

The design of buildings has a great effect on the economy, society, city planning as well as on energy and environment issues [1] [2] [3]. According to work carried out by ECBCS [4] (2002), buildings energy requirements still account for more than one third of the world's primary energy demand. The ongoing interest for the energy in buildings helped in defining standards at an international level. The 2002/91/EC European directive is related to the energy profile of the buildings and aims at increasing the efficiency of energy usage in buildings and reducing emissions. During the last decades, studies were focused on increasing building energy use efficiency during the usage period of the building's life cycle, while the stages of producing construction materials, building and demolition were given less attention. It has been shown [5] [6], that the usage period of a building consumes the biggest part of the overall exergy. Efforts aiming at the reduction of exergy consumption during the usage period resulted in an increase of thermal insulation (reduction of thermal losses), and the application of passive systems and renewable energy sources. However, if the exergy demand during the usage period decreases considerably, thus minimizing environmental impact, exergy consumption during the construction and the materials production phase become more important. It then becomes necessary to pay more attention to use of construction materials with a low environmental impact. The role of materials in the buildings energy balance and their toxicity must be taken into consideration [7]. The cost of the materials, their mechanical strength, their reliability and safety are also very important factors [8] [9]. The environmental impact of materials is directly related to the exergy that is embodied in each material [10]. The construction of buildings requires large quantities of natural resources as well as valuable exergy. Cement, steel, glass, aluminum, ceramics, synthetic materials, paints and other construction materials require a lot of natural resources and exergy for their production, transportation and use in buildings. The continuously growing exergy demand and the natural resource consumption during the usage period constitute a major challenge in the reduction of environmental impacts.

Based on the above, it is becoming obvious that the philosophy of building design changes. Constructors are becoming more interested in buildings and materials that are able to both satisfy the needs of the users and at the same time minimize environmental impact and protect the health of tenants and of the ecosystem [11] [12]. Design objectives related to a modern residence, besides handiness and aesthetics, are:

- minimization of exergy consumption for heating, cooling and domestic appliances;
- use of materials and construction elements with low embodied exergy and acceptable environmental behavior;
- good air quality.

This work examines the reduction of the exergy consumption in the buildings during the construction and use stages. The use of indicators is the most appropriate way to achieve this objective. Exergy indicators are defined in order to create reliable criteria for the characterization of building and material sustainability [13]. Exergy indicators are also used for the analysis of active and passive energy systems. The indicators are based on the definition of exergy and are related to the exergy consumption during the use period of the building as well as to the exergy which the materials embody through their production procedures. The use of exergy indicators will be applied in a case study for a new office building in Greece.

3.1.2 Exergy Analysis

The term exergy was introduced by Zoran Rant in 1953 [14] and it derives from the Greek words “external” and “energy”. Exergy is a measure of the quality of energy. It can be consumed and destroyed by any physical or mechanical system. Exergy can be described as the maximum work that can be produced from a given form of energy when it approaches its thermodynamic balance with the environment [15]. The available work that can be extracted from a source of energy depends directly on the environment state (pressure, temperature, etc). The bigger the difference between the environment state and the system state, the bigger the amount of obtainable work. Provided that there is a difference between the energy content of a system and the energy content of the environment, then energy and exergy have different values. As was mentioned before, exergy is the part of energy which can perform useful work. The remaining part of energy expresses that part of energy that can not be used to perform work, and is called anergy. The energy therefore is made up of two parts, exergy and anergy [16]

(Energy input – Anergy input) – Anergy generated = (Energy output – Anergy output)

$$(E_{in}-S_{in}T_0) - S_{gen}T_0 = (E_{out}-S_{out}T_0) \quad (1)$$

Exergy can be found in four basic forms: kinetic, potential, chemical and physical (i.e. pressure-volume and heat exchange types of work). Forms of energy such as gravity, electric and kinetic can be completely transformed into mechanical work. The exergy analysis constitutes a very important tool which provides the possibility to determine the precise point, the cause and the real size of consumption and losses of exergy. It provides the designer of a system with answers that will allow a better design and functioning of this system [17].

3.1.3 Exergy Analysis in the Building Environment

It has been estimated that the energy needs of buildings amount to more than one third of the total world energy use. It becomes apparent that there is a great potential for exergy savings in buildings. The application of exergy analysis in this sector reveals the potential to increase the total energy performance. Exergy analysis can also assist in the development and selection of new technologies aimed at lower exergy consumption, and in the quantification of the energy savings. There have been many studies in that direction [18] [19] [20]. The objective is to meet the exergy needs of buildings with low quality energy (decreased exergy) after having reduced the exergy requirements for heating and air conditioning. A different approach is the study and the classification of materials, such as the development and creation of new materials, using their exergy content as a criterion. The aim is substitution of materials, where and when feasible, which will lead to a reduction of a building’s total exergy demand and have an impact on the cost and environmental performance. Exergy analysis of renewable energy sources and their environmental impact provides direction for the use of renewable energy sources [21, 22].

Material	**Embodied Exergy (MJ/kg)**
Concrete	1.7
Reinforced steel	47
Masonry mortar	9
Bricks	2.7
Emulsion paint	3.3
Gypsum fiber board	7
Roof slab	11
Ceramic tile	3.2
PVC sheets	82
Aluminum	249
Glass	21.1
Marble	12
PVC corns	79
Light weight concrete	1.3
Epoxy resin	91

Table 1: Embodied exergy of construction materials [24]

A very important parameter that is not taken into consideration is the material production location. It is logical that domestic materials have a lot less embodied exergy and much less environmental impact compared to imported materials. Generally, the use of domestic materials decreases the exergy consumption for transport and consequently the cost of transportation. The use of domestic materials decreases the exergy consumption in the stages of collection, processing and transport of materials from the source up to their use (construction of buildings), which leads to lower environmental impact [25]. The embodied exergy of a material depends mainly on its production phase. The use of materials that require more processing, and consequently have higher embodied exergy, will increase the cost of the building.

The overall embodied exergy of the materials used in the building in Greece are shown in figure 1.

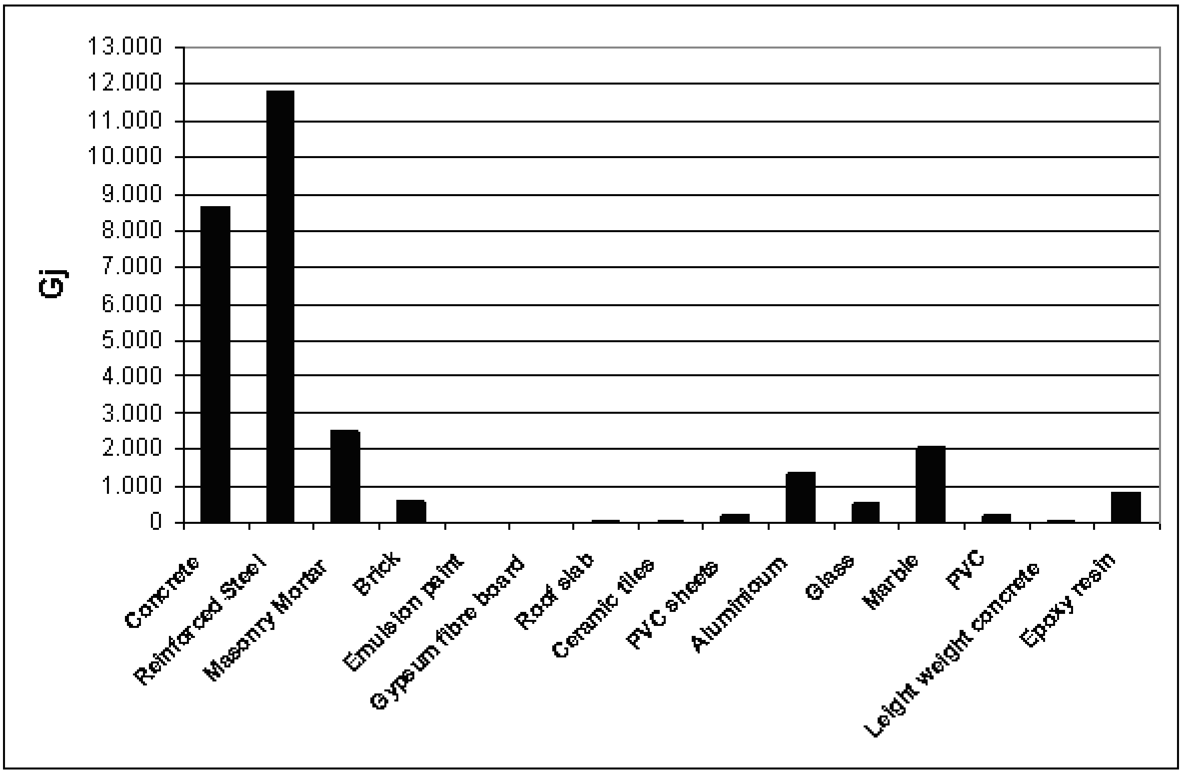

Figure 1: Overall embodied exergy of materials in the office building

3.1.4 Exergetic Indicators in the Building Environment

Generally, indicators are tools that provide information necessary for a system. They are a measure and a useful benchmark for the characterization and comparison of similar systems [26]. The use of indicators can help organize the given knowledge of any system and the mapping of complex issues such as environmental issues. Such knowledge organization, in turn, can help estimate the progress of an imminent development, as well as the overall situation and the ''trends'' of the given system. The building environment is a complex system, and thus environmental indicators are a necessity for its management and rational resource use. Environmental indicators simplify, quantify and connect the ''trends" of the data that are collected. They are very important tools because they:

- provide a measure for assessing whether the goals have been achieved;
- are very useful in enabling the general public to comprehend the achievements that have taken place in the area of environmental protection;
- help the public and governments focus on certain key-issues, affecting and bringing in line the industry;
- highlight the significance of the correlation between environmental problems and social and economic activity;
- provide awareness about environmental problems resulting from human activities;
- create a framework to collect data for environmental reports and studies.

Environmental management is based primarily on results, positive or negative, which are shown or extracted by the indicators. In order to study a system, it is possible to create a variety of indicators taking into account its features. Nevertheless, in order to be able to use the system of indicators, they must meet certain conditions [27] [28], such as:

- provide information at a level that promotes and facilitates decision making;
- be representative of the system under consideration and provide standing reliability and stability;
- list changes on an appropriate geographic and time scale;
- have clear, verifiable and scientifically acceptable data;
- be able to correlate causes and effects of problems;
- require a limited number of parameters to be established;
- be easily understood and accessible to the public.

In order to understand the use of environmental indicators an example will be provided. For a given structure, it is necessary to set the scope and target for the specific building analysis and the desired or expected results. The desired results are the construction of a building with the lowest possible exergy consumption and environment sustainability [29], [30]. For the achievement of such a goal, the following targets are set:

- the building should be able to cover the exergetic needs using several energy sources combined at an appropriate share;
- the most high-exergy yet scarce resources such as fossil and petrochemical fuels should be stored and used only in special occasions, e.g. when there is an increase in demand;
- renewable energy should be used as much as possible;
- the efficiency of the building's life cycle should be increased (this can be achieved by using reusable materials with low exergy contents);
- air quality should be a priority issue in order to protect human health and the environment.

Therefore, in order to make an evaluation of whether the above targets have been reached, it is appropriate to use exergetic indicators [31],[32],[33],[34],[35],[36],[37] such as:

- % of exergy from renewable energy sources;
- % of exergy coming from electricity which originates from renewable energy sources;
- % of the building needs that can be met by low temperature heat networks.

The aim of introducing and using exergy indicators is to increase the energy-exergy performance of a building. Efficiency can be optimized with specific interventions dictated by analysis of data based on exergy indicators. In order to choose the correct and representative exergy indicators, it is essential to collect building data such as:

- annual exergy consumption [E];
- heated surfaces [Ah];
- building surfaces [A];
- climate conditions;

- number of residences/users [p];
- materials used and their share [Yi].

Based on the above, the following exergy indicators are extracted:

- overall exergy consumption [E];
- overall exergy consumption per unit of surface [Ea =E/A]overall exergy consumption per residence/user [Ep=E/p];
- exergy consumption for heating [Eh];
- exergy consumption for heating per unit of surface [Eha = Eh/Ah];
- exergy consumption for heating per residence/user [Ehp =Eh/p];
- exergy consumption for heating per degree-days [Ehd =Eh/d]l
- exergy consumption for heating per degree-days and surface [Ehda =Eh/(dxA)];
- exergy consumption for lighting and domestic devices per residence/user [Elp =El/p];
- exergy consumption for hot water (domestic use) per residence/user [Ewp =Ew/p].

The above indicators carry a lot of information with the ability to guide research of the exergetic performance of a building. The benchmarks for these indicators are the desired results or obligations determined by the respective laws and directives. It has been mentioned that a building is part of the overall system of the environment. The building as a system interacts with the environment and has an inevitable impact. For this reason, appropriate environmental indicators, based on exergy and its consumption, are defined, in order to reduce the environmental impact from the early stages of construction and the operation of buildings. The analysis of some of these indicators follows.

During the life cycle of a building, a great part of exergy is lost during the production of the building materials and at the construction stage. An important step for increasing a building's exergetic efficiency is the reduction of entropy generation for the production of a product unit. The exergy consumption for producing a product unit (e.g. 1 kg) can be calculated using the following equation:

$$E_{pu} = \sum_{i=1}^{n}(L_{em,i} + L_{proc,i}) = \sum_{c} M_c * e_c + \sum_{i=1}^{n} E_{in,i} - E_{p,n} \qquad (2)$$

Where: E_{pu} is the exergy consumption per product unit during n process steps (pu= product unit), $\sum_{c} M_c * e_c$ is the overall chemical exergy of the raw materials used as input in the first process step, $L_{em,i}$ and $L_{proc,i}$ are the exergetic losses of emissions (and byproducts) and losses of the process i, $E_{in,i}$ is all other exergy input necessary, than $E_{in,p,i}$, that enters during the process i, $E_{p,n}$ is the exergy of the final product p,n. All terms are considered per unit of the final product p,n produced.

The total exergy required to produce one product unit, the embodied exergy, is the sum of the above indicated exergy consumptions and the chemical exergy of the product.

The indicators CEC, Cumulative Exergy Consumption, and the Production Efficiency of Material (%), also focus on the interaction between the production chain and the environment. Attention should be paid to the resources that have to be extracted from the ecosystem and the environmental impact of their corresponding emissions. In combination with the process and production performance, three variables must ultimately be evaluated: the environmental impact of energy source exploitation and raw materials excavation, the technological performance, and the emissions' environmental impact. The CEC and the production chain efficiency for several industrial products, many of which are building construction materials, are shown on table 2.

Product	**CEC (MJ/kg)**	**Production Efficiency (%)**
Polystyrene	91.9	45.7
Electricity	4.17 (from coal)	24
Copper	147.4	1.4
Zinc	198.9	2.6
Aluminum	250.2	13.2
Methanol	73.1	30.7
Acetylene	236	20.7
Propane	61.6	79.3
Concrete	1.7	0.0
Paper	59.9	27.5
Glass	21.1	0.8
Polyethylene	86	54.1

Table 2: Embodied Exergy of materials and their production efficiency

The three factors mentioned before can be used as quantifiable environmental indicators of sustainability. To investigate the environmental ''friendliness'' of the technological processes, it is necessary to study the nature of the raw materials which are used. These resources can be divided into two categories: those that are produced naturally at a rate at least the same as that of consumption, and the non-renewable resources which are consumed by the industry at a rate greater than they are produced naturally. The factor **''α''** expresses the ratio of renewable resources to the total resources used in a production process.

α = Renewable Resources Used / All resources used

The total efficiency **"η"** describes the technological efficiency and is related to the CO_2 emissions' environmental impact. These two environmental indicators **''α''** and **''η''** can be combined to form S [38]:

$$S=0,5*(\alpha+\eta) \quad (3)$$

The indicator S has a value between 0 and 1. When it approaches 1, the process is more exegetically efficient and the material produced has a smaller related CO_2 emission to the environment.

For a better understanding of the indicator S, the production of ethanol through three different processes is shown in table 3. The processes examined are: production from fossil fuels by hydration of ethylene, production from biomass through fermentation, and hypothetical production by use of electric energy from solar cells, hydrolysis and the chemical reaction with hydrogen and carbon dioxide.

Manufacturing Process	**α**	**η**	**S**
From fossil resources	0.0002	0.365	0.183
Fermentation biomass	0.998	0.00694	0.502
Reaction with H2/CO2	0.911	0.0645	0.488

Table 3: Indicator S for ethanol

As mentioned, choosing appropriate environmental indicators is the key to assessing and reducing the environmental impact of a building. It is important to avoid problems of complexity and sorting of indicators, as well as problems of integrating different environmental impacts in a small number of indicators (as is generally the case with Life Cycle Assessment, LCA). In order to overcome such difficulties, the concept of exergy is introduced to assist in the introduction of the environment indicator of **"eco-efficiency"** which is defined as the price of the product divided by its environmental effect during its entire life cycle.

Eco-efficiency = Price of a Product / Environmental Impact of a Product (4)

The problem with indicators of this kind is that there are no formal rules for recognition, measurement and presentation of information on the environmental impacts of a system or of a compilation of two or more systems. It is also important that there are no rules that combine environmental information with financial data. After all, the currently existing forms of this indicator focus mainly on adequate quantification of the denominator. Another problem that appears in the indicator of ''eco-efficiency'' is that the two 'parts' of the ratio are measured in different units. To avoid this problem, the following formula can be used to define the indicator e:

$$e = \frac{T_p}{C_p} \qquad (5)$$

Where C_p is the exergy of all natural and recycled resources that are consumed in all stages of the production process of a product p plus the exergy that is related to the exergy losses occurring in all production process steps, and T_p is the price of the product expressed in exergy units (GJ).

The above indicator e expresses the quotient of the exergy of the product related to its price and all necessary exergy inputs to produce the product in a way friendly to the environment.

A relationship between exergy and price of a product can be easily obtained. While manufacturing these products, industries incur costs for raw materials, machinery, energy use, transport etc. The clients on the other hand buy the product and pay a price. Thus, in order to relate this price unit to exergy units, the following formula is suggested:

$$e_c = \frac{V_p / P_a}{C_p} \tag{6}$$

Where P_a is the average value of one GJ of energy in €/GJ, V_p is the product price in €, and C_p is the total exergy input of the production process plus the exergy that is related to the exergy losses occurring in all production process steps. The numerator is the amount of energy to be bought with the price of the product that will be paid by the client. The average price for a GJ of exergy can be calculated, with reasonable approximation, from the average use of all energy sources and their cost for a GJ.

$$P_a = \sum R_i * P_i \tag{7}$$

Where R_i is the share of an energy source i, and P_i is the cost of a GJ of that source i. The eco-efficiency indicator e_c combines the economic and environmental performance of producing and selling (i.e. value) a product. However, if a product has an eco-efficiency value in the range of 0 to 1 it is unsustainable because the exergy used for producing the product is greater than exergy of the product as valued by society. If the indicator value is over 1, then the higher the value the greater the sustainability of the product from an economic-environmental point of view [38]. The indicator e_c contains the subscript ''c'' that derives from the cost and indicates the economic nature of the indicator introduced by the term Vp, which is the value of the product on the market. The base of the indicator e_c is economic in nature and requires a somewhat stable embodied exergy of the particular product considered. Therefore, in order to complete a useful set of eco-efficiency indicators, the urgency of efficient production of products with the related effect of reduction of the embodied exergy must be made visible. This can be done by the introduction an indicator that compares the exergy of the product E_p to C_p, already defined earlier.

$$e_x = \frac{E_p}{C_p} \tag{8}$$

The aim is to have this indicator e_x as close as possible to one for each product or material, which would indicate a decrease in embodied exergy related to exergy losses and emissions. A value closer to one compared to the older production process indicates a successful process improvement [39].

A very important measure and indicator of the sustainability of a building is the material's recycling and reuse potential after the demolition stage. Reuse is a measure of saving resources and energy. The reuse ratio (kg of material reused compared to the total mass of material), which is not always clearly defined, is a widely used indicator in demolition processes in buildings. This indicator contains useful information about reusability for different types of materials. A high reuse ratio is the desired result, but its related environmental impact it is not always clear [40].

There are many terms that can be used for the reuse of building material. In order to demonstrate the impact of reuse on the performance and sustainability of a building, the parameter to look at is the exergy use.

“Reuse” can be divided into three subcategories considering the quality of the material:

1. Recirculation: the immediate reuse of a material when its internal structure is not affected or contaminated, e.g. the doors and windows;
2. Upgrading: the extra energy required to reset the internal structure of materials at levels similar to those before their use. Upgrading is divided into recycling and partial recycling where partial recycling refers to materials whose structure does not correspond entirely to the structure they had before the use [41]. Examples of upgrading are recycling or partial recycling of metal products such as steel and aluminium;
3. Succession: the reuse of a material or product whose internal structure is degraded compared to the original. An example is the cutting and breaking of concrete to be used in a mixture of aggregates for road construction.

Usually, after a building’s demolition, another serious question arises: degradation and disposal or degradation and reuse? In many cases, a product is more cost and energy intensive to recycle or reuse rather than to produce it from the outset. Here the ethics of recycling and reuse must be imposed. The criterion for this decision is to compare the embodied energy the material has when it is produced for the first time to its energy when it is recycled. An example is shown in figure 2.

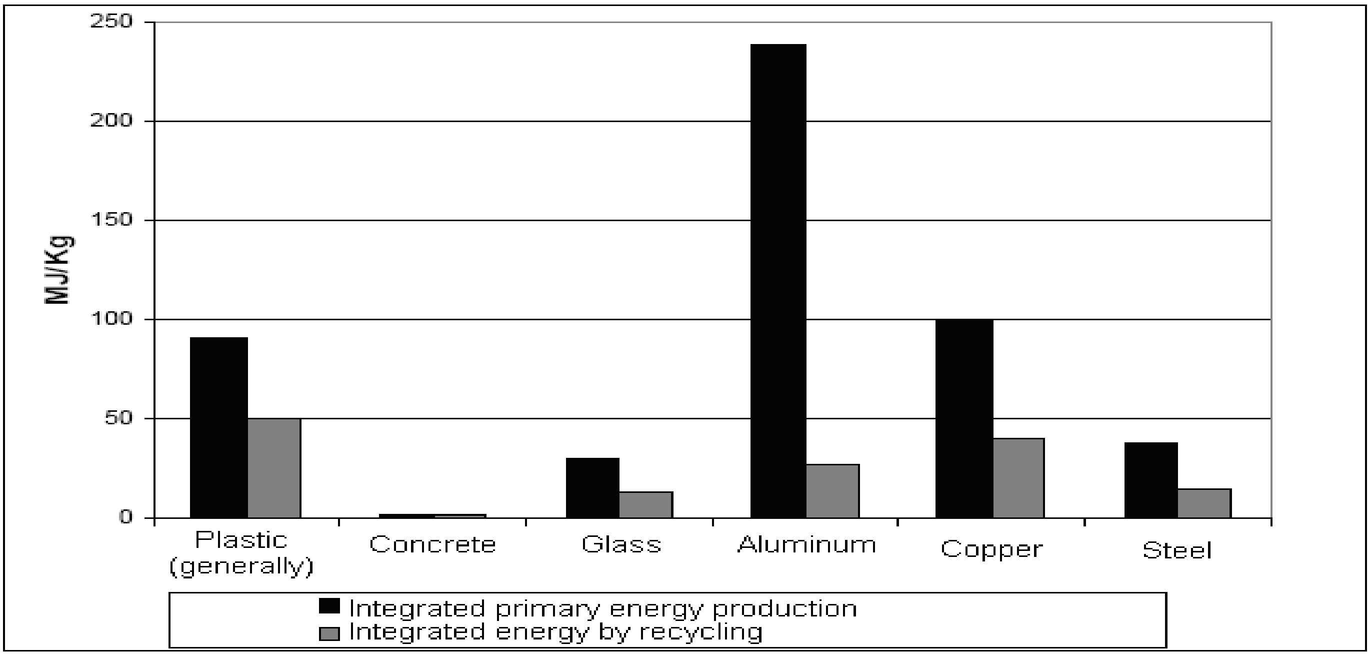

Figure 2: Embodied Energy for ordinary building materials [42]

Generally, materials with a minimum industrial production process time are easily recycled. Materials that have undergone substantial processing (high temperature and complex chemical reactions) are very difficult to recycle. A typical example of this kind of material is plastic. Biodegradable materials are preferred.

In many cases, the materials used in today's buildings come from processed waste material from other processes. So far, sawdust has been widely used for the production of fibroma and particle boards. Other inventive materials, such as feathers, are used to manufacture American concrete. Also, many efforts are made to absorb other materials on the building so that the building could become a store of waste material. This will make the extraction or production of new materials unnecessary. In many buildings, straw is already used in many components, for example to build walls.

In Greece fly ash produced as waste from power plants is used as construction material. The fly ash is used as raw material in concrete production. Its toxicity limits its use in structures that are in direct contact with humans, and it is not used in inert concrete for the construction of buildings).

For existing buildings, the materials that can be recycled are:

- components of stones without mortar;
- some insulation (in good condition);
- timber construction;
- plaster objects (i.e. plasterboard);
- wooden panels;
- building components such as doors, windows and sanitary ware and furniture.

Bricks, cement and concrete are not easily recycled or reused in new construction. However, it is possible to treat and use them as materials in horizontal surfaces and road construction.

The reuse of building materials has been proven to reduce 95% of the embodied energy of materials that would otherwise be lost as waste (figure 3).

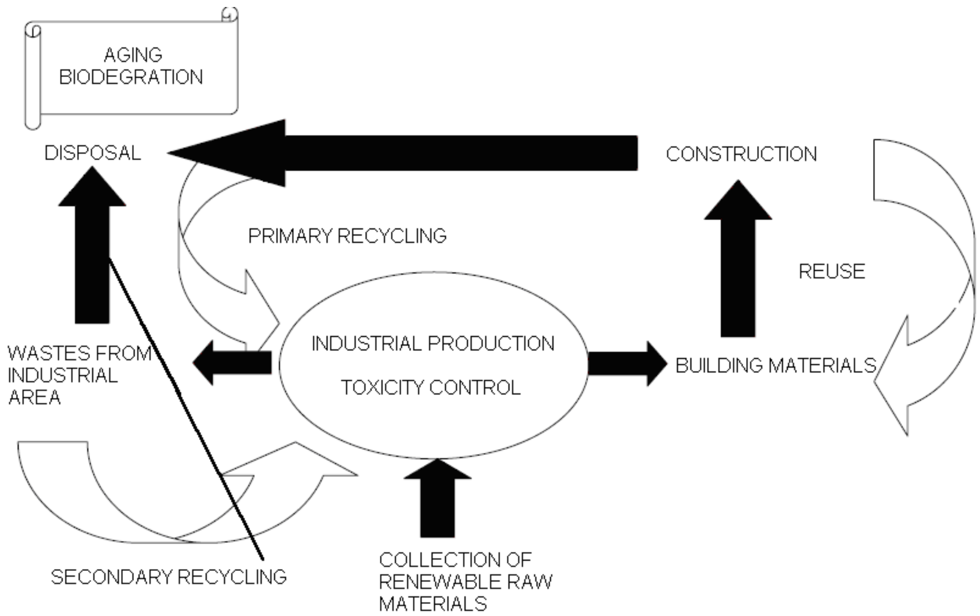

Figure 3: Flow chart of the recycling of materials [30]

3.1.5 Exergetic Analysis of an Office Building

Life Cycle Assessment is a useful tool for evaluating the environmental impact of buildings as well as the use of energy and natural resources. Research has focused on understanding the energy use during the utilisation stage of the building. In order to understand the overall environmental impact of a building, it is important to consider all stages of its life cycle, such as the production of construction materials, construction or pre-fabrication, building use and demolition. To assess the environmental impact of a complex system, like an office building, a good understanding of the impact of each 'part' of the building is required.

The objective of the following example is to examine the exergetic and environmental efficiency of an office building in Athens. The weight and type of material used has been taken into account[43].

The life cycle of the building consists of three individual stages: construction, use and demolition. The construction stage consists of the manufacturing and transportation of all construction materials and the construction of the building. The use phase includes all activities related to the use of the building for a life cycle of 80 years. These activities include all the exergy consumed in the building including the amount consumed for heating, air conditioning and lighting. The demolition stage of the building includes the transportation of materials generated for recycling or landfill.

Material Data

The materials used for the construction of the office building are: concrete, steel, bricks, masonry mortar, insulation materials, aluminium, glass, marble, gypsum fibre board, paint, PVC, epoxy resin, roof slabs, ceramic tiles, light weight concrete, metals [43]. Table 4 shows the overall mass and the percentage of each material used in the building relative to the total building mass. The total exergy content of all materials used in the building is shown in figure 4 and table 6.

The embodied exergy of material used for construction is shown in table 5. It is evident that of all materials, aluminium has the greatest embodied exergy due to the large amount of electricity required for its production. On the other hand, the smallest exergy content is in the lightweight concrete roof due to the amount of cement it contains. Significant amounts of exergy are also embodied in epoxy, polyvinyl chloride and steel. The transportation exergy is not included in these values, but can significantly add to the embodied exergy when transportation distances are very large.

Material	**Mass (Kg)**	**Percentage %**
Concrete	5,080,270	83.22
Reinforced steel	251,255	4.12
Masonry mortar	275,128	4.51
Bricks	229,654.30	3.76
Emulsion paint	1,458	0.02
Gypsum fibre board	3,713.43	0.06
Roof slabs	5,772.53	0.09
Ceramic tiles	13,460.52	0.22
PVC sheets	2,754.41	0.05
Aluminium	5,443.84	0.09
Glass	26,828.10	0.44
Marble	172,964.30	2.83
PVC corns	2,763.77	0.05
Light weight concrete	24,178.70	0.40
Epoxy resin	8,831.70	0.14
Sum	**6,104,477**	**100.00**

Table 4: Overall material masses and percentage of participation [43]

Material	**Embodied exergy (MJ / kg)**
Concrete	1.7
Reinforced steel	47
Plaster	9
Bricks	2.7
Lactic paint	3.3
Plasterboard	7
Slate	11
Ceramic tiles	3.2
Polyvinyl chloride sheets	82
Aluminium	249
Glass	21.1
Marble	12
Grains polyvinyl	79
Concrete roof	1.3
Epoxy glue	91

Table 5: Embodied exergy of building materials

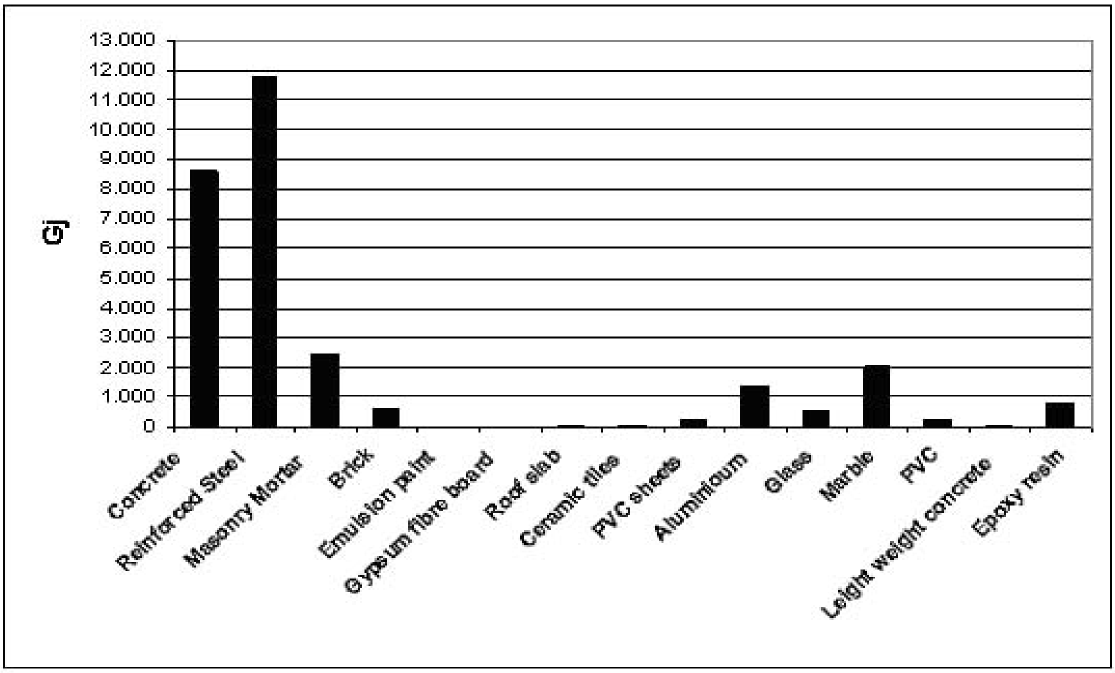

Figure 4: Total integrated exergy of building materials

Material	**Embodied exergy (MJ)**
Concrete	8,636,459
Reinforced steel	11,808,985
Plaster	2,476.152
Bricks	620,066.61
Lactic paint	4,811.4
Plasterboard	25,994.01
Slate	63,497.83
Ceramic tiles	43,073.664
Polyvinyl chloride sheets	225,861.62
Aluminium	1,355,516.16
Glass	566,072.91
Marble	2,075.5716
Grains polyvinyl	218,337.83
Concrete roof	31,432.31
Epoxy glue	803,684.7
TOTAL	**24,408,345**

Table 6: Total embodied exergy of the building material

Allocation of Exergy Consumption

The use stage of the building includes the exergy consumption for heating, air conditioning and lighting. The life span of the building is 80 years. The consumption of electricity and natural gas was based on Greek climate conditions and literature data. Taking into consideration these consumptions, the best scenario was estimated. The heating needs were met by natural gas combustion while electricity met lighting and cooling needs. Finally, considering that the exergy efficiencies (coefficient of energy quality) for these two energy carriers are 98% and 100% respectively, the exergy consumptions was calculated (table 7 and figure 5)

Natural Gas (GJ)	Electricity (GJ)	Sum (GJ)
68,399	32,400	100,799

Table 7: Exergy consumptions [31]

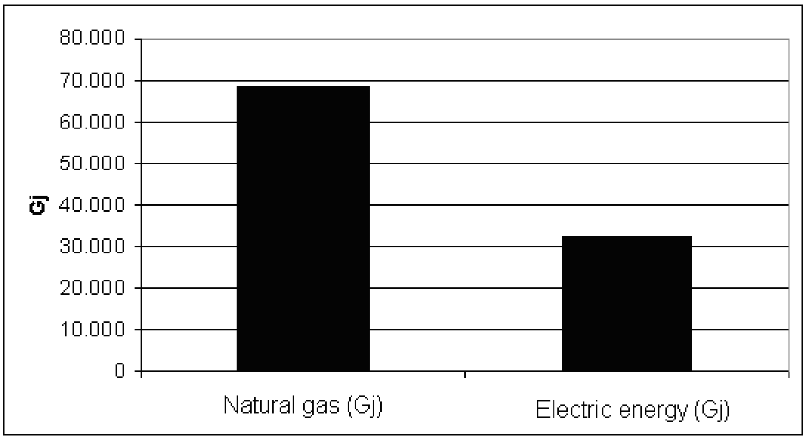

Figure 5: Exergy consumption during use

Based on the figures in table 8, it becomes apparent that 22% of exergy is used during the construction phase while 78% goes to the use phase (figure 6).

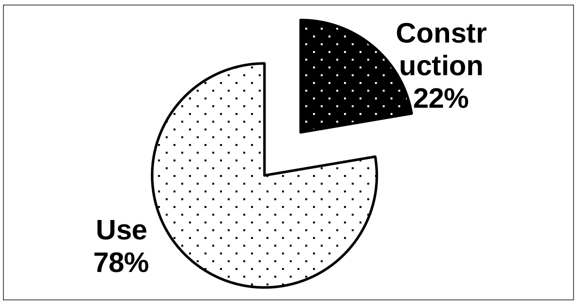

Figure 6: Allocation of exergy consumption

Material	**CEC (MJ/kg)**	**Pa (Euro/GJ)**	**Vp (Euro/kg)**	**Fuel**	**Eco**
Concrete	1.7	1.625	0.043	lignite	15.565
Concrete	1.7	0.51	0.043	chopped tyres	49.596
Reinforced steel	47	16	0.869	natural gas	1.155
Reinforced steel	47	27.8	0.869	electricity	0.665
Masonry mortar	9	7.53	0.271	stone coal	4
Bricks	2.7	21	0.12	diesel	2.11
Bricks	2.7	27.8	0.12	electricity	1.598
Bricks	2.7	16	0.12	natural gas	2.78
Emulsion paint	3.3	16	4	natural gas	75.75
Gypsum fibre board	7	7.53	0.522	stone coal	9.9
Roof slabs	11	27.8	2	electricity	6.54
Ceramic tiles	3.2	16	0.15	natural gas	2.929
PVC sheets	82	16	20	natural gas	15.243
Aluminium	249	27.8	4.33	electricity	0.625
Glass	21.1	14.99	0.55	crude oil	1.738
Glass	21.1	16	0.55	natural gas	1.629
Glass	21.1	27.8	0.55	electricity	0.937
Marble	12	21	4	diesel	15.87
Light weight concrete	1.3	1.625	0.043	lignite	20.35
Epoxy resin	*91*	*16*	*9*	*natural gas*	*6.18*

Table 8: Material data and Eco-efficiency

It is important to note that in these calculations the consumption of exergy for possible renovations during the building's life cycle were not taken into consideration. It becomes clear that even though the repentance of exergy used during the construction phase is only 22%, the use of ecological material will have a big impact on the total exergy picture.

Estimation of Eco-efficiency indicators

Based on embodied exergy data of the materials presented in the previous sections, the eco-efficiency indicators are calculated. Concrete, which is used rather extensively, will have different eco-efficiency indicators based on the method of production. Its eco-efficiency indicator is 70% lower when it is produced using lignite as a fuel than when it is produced using old car tires as fuel.

These calculations are presented in figure 7 and table 8.

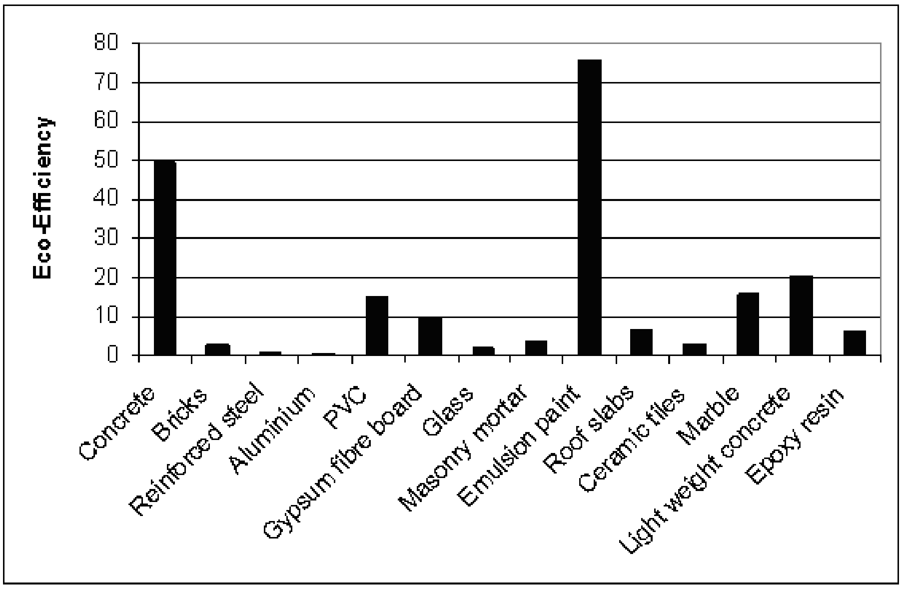

Figure 7: Eco- Efficiency indicators

Using the indicators and the percentage share of each material, the overall Eco-efficiency indicator (E_k) of the building is calculated. The overall indicator states the environmental profile of the building and constitutes a measure for the comparison with other buildings.

The overall indicator is calculated with the formula:

$$\sum_{i=1}^{n}(e_{c,i})x(p_i) \qquad (9)$$

Where $e_{c,i}$ is the Eco-efficiency indicator of a material i, p_i is the share of the material i, and "n" is the number of materials used in the building. In this case study, two indicators are calculated. One is for materials with a more sustainable production procedure and the second is for materials with less sustainable production procedures (table 9). The difference between the two figures (65%) is indicative of the importance of the production procedures.

E_{K1}	E_{K2}
42.2023507	13.8135969

Table 9: Overall indicators

Renewable Energy Use

The use of Renewable Energy in buildings is an issue that is of great importance for the reduction of greenhouse gases and the management of natural resources. The use of Renewable Energy Sources (RES) in buildings may cover up to 70% of energy needs by satisfying hot water and electricity needs.

The use of renewable energy is investigated under several scenarios considering the energy needs of the office building. The environmental impacts are also analysed. The scenarios focus on the satisfaction of 10%, 20%, 30%, 40% and 50% of the energy needs during the use stage. These percentages translate to 7.8%, 15.6%, 23.4%, 31.1% and 38.9% respectively of the total energy needs during the construction and use phase (table 10).

Percentage of RES during the use stage	**10%**	**20%**	**30%**	**40%**	**50%**
Renewable energy use [GJ]	10,189.63	20,379.26	30,568.88	40,758.50	50,948.14

Table 10: Renewable energy utilization during the use stage of a building

The total exergy consumption in the building is split into 78% going to the use phase and 22% going to the construction phase. These scenarios will lead to the reduction of environmental impacts. The distribution of renewable energy use is shown in figure 8.

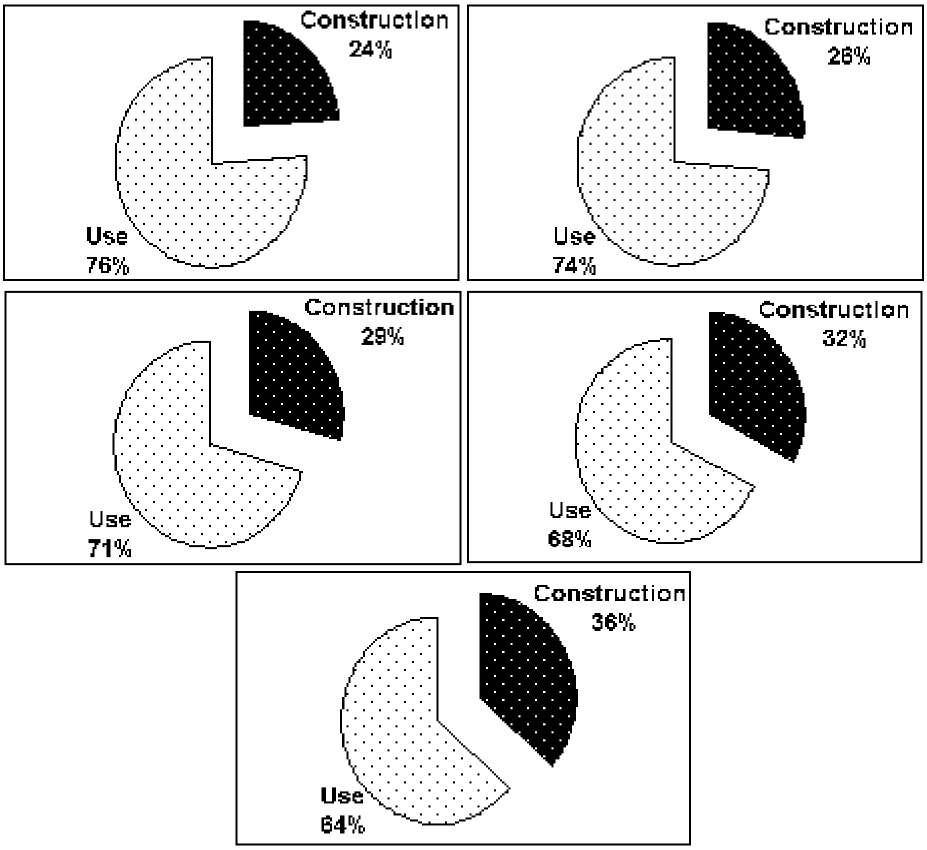

Figure 8: Interaction in the use of RES scenarios

The effect of renewable energy use on the environmental impact is shown in figure 9. The use of renewable energy has a direct effect on the environmental impact during the phases of use and construction. The environmental impacts during the construction phase increase as the percentage of renewable energy increases. This makes the use of materials with lower environmental impact more important and leads to the search for new environmentally friendly material.

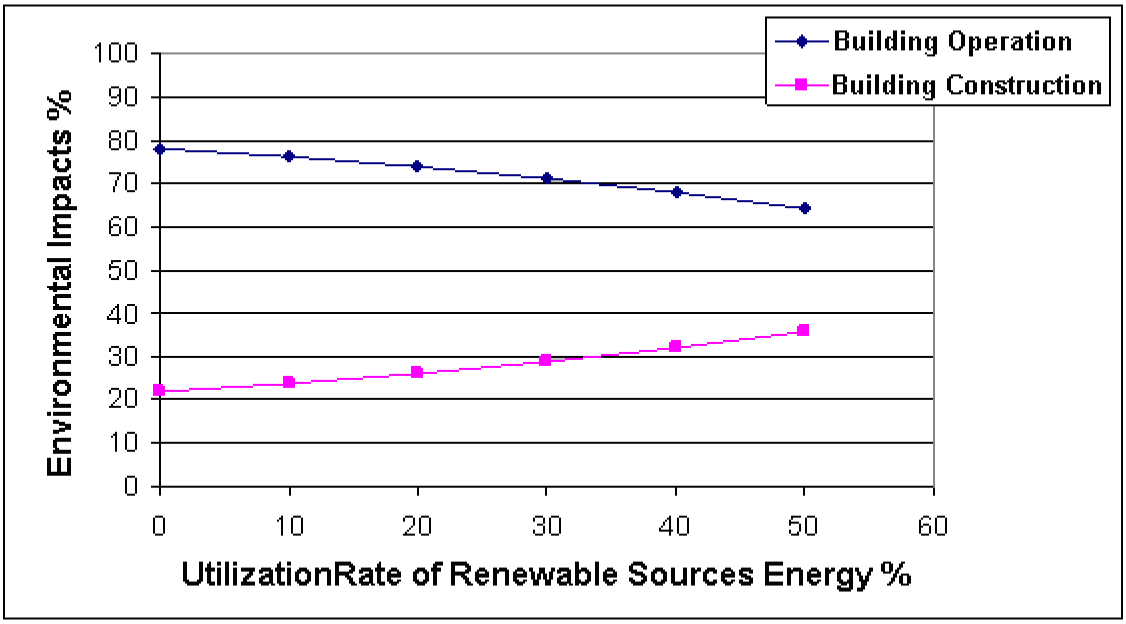

Figure 9: Changes in environmental impact

3.1.6 Conclusions

This work aims to provide an overview of the possibilities and advantages that exergy analysis offers to the building sector. Analysis of data for an office building built based on the guidelines applied in Greece revealed that 3/4 of the building's exergy consumption, during its 80 year life, occurs in the use period (heating, cooling, lighting), while the remaining 1/4 is related to the construction period (material extraction/process/transport).

As the exergy performance during building's use period was improved, the interest turned unavoidably to the development of more sustainable materials and construction in general. The construction materials' embodied exergy and the quantity of this exergy depends on the excavation procedure to extract raw materials, the production procedure of building materials and the transportation. All this embodied exergy is proportional to the environmental impacts of the material. Concrete is used most extensively (83%) in the analyzed case, but has the smallest embodied exergy (1.7 MJ/Kg) among the materials considered, while aluminum has the highest embodied exergy (249 MJ/Kg) because of the large energy demand during its production.

The exergy indicator Eco-Efficiency is a good measure of sustainability for each material. Its value is directly related to the fuel used. The values of this indicator are high for concrete and emulsion paint, while these values are low for aluminum, steel and bricks. Taking into consideration the more sustainable production procedures for each material, a difference of 65% exists in the overall exergy indicator with the less sustainable procedures. This could be translated to 65% less environmental impact. This difference can be seen in the case of the concrete production that employs used car tires as energy feedstock. Hypothetical scenarios of employing renewable energy sources are also examined for the building. The renewable sources reduce the environmental impact by minimizing the exergy consumption. However, their use leads to a small increase in the non-indigenous materials with higher embodied energy.

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3.2 The Technological Aspect of Sustainability and Parameters to express that Aspect

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3.2.1 Introduction

As we now realize, many of our interactions with the environment have a negative effect on that environment. The exergy we need for the production of biomass comes mainly from solar radiation. The first stage in the production of plant-based biomass is photosynthesis. The interaction of solar radiation with two different pigments leads to the release of formerly bonded electrons to produce active hydrogen and oxygen from water. This active hydrogen (NADH) is used to reduce carbon dioxide and to form all kinds of substances present in biomass. Examples of such substances are proteins and different kinds of sugars, often in the form of polymers (e.g. cellulose, lignin), oils, and plant specific substances (e.g. fragrants). During plant life, exergy stored in many of these substances is used to drive all kinds of processes. It becomes available by break down and oxidation leading to the emission of carbon dioxide and water. Animals are unable to extract exergy from solar radiation themselves and must feed on plants.

Fossil fuels are derived from all kinds of plant and/or animal based materials, either directly or indirectly by making use of exergy from solar radiation. They are now the main sources of exergy available and used on earth. Their formation started when oxidation of the biomass was not longer possible e.g. when the biomass was covered by water and/or earth crust material. Due to geological processes this material was transported deeper within the earth crust. At appropriate combinations of pressure and temperature, conversion to form fossil fuels occurred. These fossil fuels are the main exergy source used to drive our processes in the techno sphere. Most of the organic chemical products used in our society are produced from fossil fuels. To produce power, fossil fuels are combusted leading to emissions in the environment. Main emissions are those of carbon dioxide and water. Water can be “easily” taken up in the natural water cycle. This is not the case for carbon dioxide in the natural carbon cycle. The concentration of carbon dioxide in air increases relatively fast, as does the concentration of carbon dioxide in (sea) water. In addition, due to the formation of calcium-(hydrogen)-carbonate and calcium carbonate, the calcium concentration in water decreases. Our climate will change in accordance with what we have seen in the past. In the Carbon period the carbon dioxide concentration in the atmosphere was much higher than today, also the mean temperature on earth was higher. This led to a vast increase in the growth of biomass and many of our fossil fuels stem from that period.

Other elements present in fossil fuels are also released, when the fossil fuels are combusted, in gas form such as sulphur oxides, nitrogen oxides, hydrogen chloride (acid rain), in liquid form, often substances dissolved in water, and as solids (ash). All these elements were taken up from the soil (sea water) where the plants had been growing.

The speed with which we combust our fossil fuels is many orders of magnitude larger than the speed of their generation and storage. This leads to disturbances in the natural cycles with many negative effects e.g. a decrease in biodiversity. This decrease in biodiversity is a very good indicator for the negative effects of human activities. What we can learn from the interdependences in living nature is that all cycles are closed and in a “steady” competitive state. Through evolution there is a development of nature, also leading to new and more adapted, species. Large-scale volcanic activities and the impact of a collision of our planet with material from the universe can lead to large disturbances of the natural system. Within this context, biodiversity can be used as an indicator for the quality of the ecosphere. As we have seen, the use of fossil fuels leads to disturbances in the steady state of the essential elemental cycles and to a decrease in the quality of the ecosphere and thus to a decrease in biodiversity. Many other substances produced in our techno sphere have negative effects on the ecosphere, e.g. many crop protection agents, especially those used in the past, could accumulate on the top of the food chain and lead to mass starvation of among others birds of prey. A characteristic of these types of substances is that they do not occur in the ecosphere and that microorganisms are not able to feed upon them. Only few examples are given, but it is still clear that one can formulate a strict boundary condition for our actions in the techno sphere. All substances produced in the techno sphere can be divided in three groups: first, substances known to be toxic and those for which it is not (completely) known what effect they can have in the eco sphere; second, substances playing a role in natural cycles and; third, substances such as those making up the composition of the soil and the different types of soil themselves.

For the substances mentioned first we must critically evaluate if these substances are essential to us, and, if so, whether they can be replaced by others, preferably not harmful to the ecosphere. When this is not possible, we must avoid that these substances come in the ecosphere. This can be expressed with the term: “zero emission”. This is a very severe but essential condition. For the second type of substances we must be careful not to overburden the natural cycles. The third type of substances is allowed to come in the ecosphere if the quality of the soil remains the same or can be improved.

Fossil fuels are a source of exergy. When we make use of this source, e.g. to produce electricity in a power plant, part of the exergy is irretrievably lost. A substantial part of these losses are related to the energy conversion involving thermal energy. When released, thermal energy leads to an increase in the temperature of the surroundings of the system. When the power originates from fossil fuels (or nuclear energy) we speak of thermal pollution. In the process of harvesting solar radiation, we have a possibility to emit the thermal energy to the universe in a way similar to that before the harvesting process was implemented. Only in the thermodynamically limiting case of reversible processes will no exergy be lost.

In order to change (produce) something in the techno sphere, we must use appropriate driving forces. These driving forces necessarily lead to exergy losses, and, when based on the use of material exergy sources on earth, to a decrease of our exergy stock available on earth. The consequence of this notion is that, preferably, we must use solar radiation as a source of exergy to make conversions possible in the techno sphere. However, in order not to disturb the ecosphere, solar radiation must be harvested in such a way that the optical characteristics of the surface area related to this harvesting process are not changed. Furthermore, the materials used for the production of the devices needed for this harvesting process must comply with the requirements for the use of substances mentioned before. As will be clear, we must try to mimic the first stage of the photosynthesis process to produce electricity. In addition, this harvesting process must not have a negative effect on biodiversity. When these conditions are all fulfilled, the production of electricity will not have negative effects on earth, while the use of the remaining exergy stocks can then be reduced substantially, and finally (nearly) completely eliminated.

It is important to realize that we must make use of our exergy sources to drive the processes in our techno sphere. Due to the preferable use of exergy originating from solar radiation and the necessary condition to maintain, and possibly increase, the level of bio diversity, we must make use of this exergy in such a way that the total amount of exergy necessary is as small as possible. As a consequence, the exergy losses must also be minimized.

Based on the notions mentioned before, we are now able to define three parameters to characterize the technological aspects of sustainability. This will be done in the next sub-item.

3.2.2 Three parameters to characterize the technological aspects of sustainability

For an overview of the literature referring to sustainability parameters see Swaan Arons de et al. (2004). Figure 1 presents a schematic overview of material-based interactions between techno sphere and ecosphere, indicated by thin arrows, and of exergy. The exergy originates from the sun and is finally emitted (nearly) completely from ecosphere and techno sphere – with much less exergy (nearly zero exergy on earth, when we have realized a sustainable techno sphere). The flow of the exergy originating from solar radiation is indicated by the wide black arrows.

In the techno sphere, substances absorbed from the ecosphere, e.g. by mining activities or harvesting, are used as such or are treated further to produce products necessary in our society. In a sustainable techno sphere the extraction of non-living material from the ecosphere will be reduced strongly compared to the actual situation. This is indicated by the arrow resource extraction, from eco sphere to a production process, as shown in figure 1. This reduction can only be realized when materials are recycled in the techno sphere with an as small as possible exergy input. To achieve this, products must be made from as few as possible materials that, after their lifetime, can be used for other purposes and that can be separated easily, preferably mechanically, from each other. In this way, the exergy losses related to production, use, and recycling can be minimized. Only those substances that do not over burden the natural cycles and contribute to maintaining the quality of the soil (and preferably to an increase of bio diversity) can be recycled to the ecosphere. Furthermore, substances such as those making up the composition of the soil and the different types of soil themselves can be returned to the ecosphere with proper care. Substances known to be toxic and those for which it is not (completely) known what effect they can have in the eco sphere are not allowed to be applied in and/or emitted to the eco sphere. These can be called the three sustainability criteria for materials. This interaction is indicated by the arrow, from the techno sphere to the eco sphere, with the description: closure of natural cycles, as shown in figure 1.

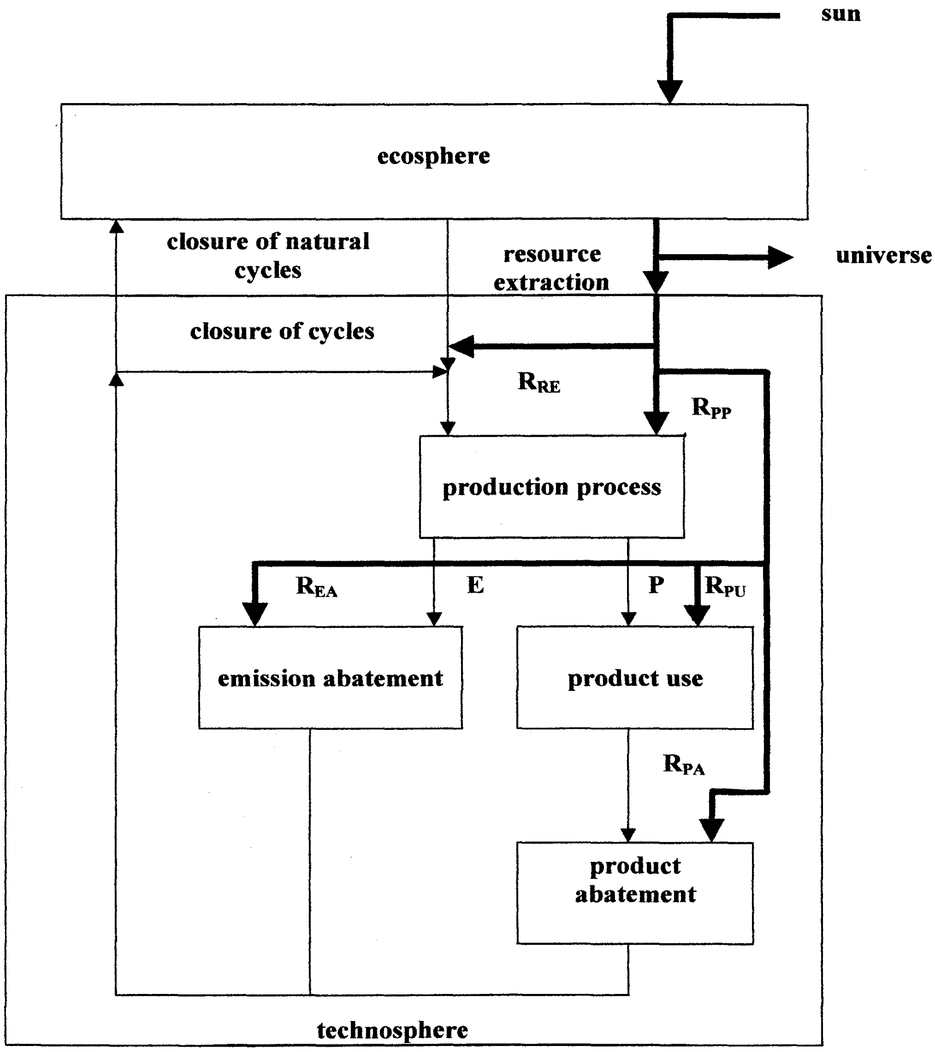

Figure 1: Schematic overview of a production process in the techno sphere in interaction with its surroundings (the ecosphere). In a sustainable situation the sun must be the exergy source to drive all processes in the techno sphere.

In the production process, only a minimal amount of substances must be used to avoid unnecessary mixing and separation, preferably without resource extraction from the ecosphere. (Nearly) all material inputs of the process are recycled within the techno sphere into production processes where (part of) these material inputs are (part of) the feedstocks. The amount of exergy necessary to drive the Production Process is indicated by R_{PP}, and the amount of exergy for Resource Extraction and their conversion (taking care to comply with the boundary conditions mentioned before) to substances to be used as input is indicated with R_{RE}.

The production process has two different outputs: the product(s) and the emissions. During Product Use, exergy can be necessary for use, maintenance, and repair. This amount of exergy is indicated in figure 1 by R_{PU}. When the product can no longer be used, the product must go to the abatement process. Here, the product is disassembled and reused as directly as possible in the techno sphere and the mentioned sustainability criteria for material emissions must be fulfilled.

The exergy necessary for this Product Abatement process is indicated by R_{PA}.

The emissions, all other substances than the product(s), are treated in an emission abatement process in such a way that they can be used in the techno sphere or that they can return to the ecosphere. This is only allowed when the three sustainability criteria for materials are fulfilled: they do not over burden the natural cycles, contribute to maintaining the quality of the soil, and preferably to an increase of bio diversity. Furthermore, substances such as those making up the composition of the soil and the different types of soil themselves can be returned to the ecosphere with proper care.

The amount of exergy necessary for this Emission Abatement process is indicated with R_{EA} in figure 1.

In a sustainable techno sphere it is of importance to drive our processes with exergy as directly obtained from solar radiation as possible. For example, electricity produced in PV cells or from (parts of) biomass. This exergy is defined as “renewable” exergy. The first parameter is the fraction of “renewable” exergy used as input in the process considered. This parameter is defined as the amount of solar exergy of e.g. electricity and biomass divided by the sum of this amount of renewable exergy and all other amounts of exergy and all other amounts of exergy present in these resources not “directly” originating from the sun, such as fossil fuels.

The first parameter is called the renewability parameter α. α is the fraction of renewable input of the total exergy input, for the production process indicated in figure 1, and is defined as:

$$\alpha \equiv \frac{R_{input,ren}}{R_{RE} + R_{PP}} \tag{1}$$

The term R_{RE} is the total amount of exergy to produce resources from the ecosphere, used as input in the production process. R_{PP} is the amount of exergy needed to drive the production process. $R_{input,ren}$ is the total amount of renewable exergy, as defined before, compared to the total exergy input of the production process. When all exergy input is renewable, the renewability parameter will be 1.

The second parameter is β. β is the exergy efficiency of the process considered. For the production process β is defined as:

$$\beta \equiv \frac{R_{product(s)}}{R_{production}} \tag{2}$$

$R_{product(s)}$ is the amount of exergy present in the product(s) and $R_{production}$ is the total amount of exergy input of the process. In the case considered, $R_{production}$ is defined by:

$$R_{production} \equiv R_R + R_{PP} \tag{3}$$

In this equation R_R is the exergy value of the resource(s) used as input for the production process. As mentioned before, in the thermodynamic limiting case of reversible processes, no losses in the production process are possible and the exergy efficiency of the production process is then 1.

The third parameter is the environmental compatibility parameter γ. γ is defined as:

$$\gamma \equiv \frac{R_{product(s)}}{R_{product(s)} + f_{ET,RE} * R_{RE} + f_{ET,CUD} * R_{CUD} + f_{ET,EA} * R_{EA} + f_{ET,PU} * R_{PU} + f_{ET,PA} * R_{PA}} \tag{4}$$

The factor $f_{ET,RE}$ is the quotient of the exergy input needed for the emission treatment processes, when resources are extracted from the ecosphere, and the total amount of exergy input needed in the resource extraction process (R_{RE}). The factor $f_{ET,CUD}$ is the fraction of the exergy input needed for the emission treatment processes related to construction, use, and demolition of the production facilities, and the total amount of exergy input for all these activities (R_{CUD}). The factor $f_{ET,EA}$ is the quotient of the exergy needed for the emission treatment processes with respect to the total exergy input of the emission abatement process (R_{EA}). The factor $f_{ET,PA}$ is the quotient of the exergy needed for the emission treatment processes related to product use and the total exergy input for the use phase (R_{PU}). The factor $f_{ET,PU}$ is the quotient of the exergy needed for the emission treatment processes related to the product(s) abatement processes and the total exergy input for these processes (R_{PA}). In a completely sustainable situation, all five factors defined before will be zero and the environmental compatibility parameter γ will be 1. The R-values are exergy values and must be expressed in, for example, W/kg or W/mole.

Because we have made use of the exergy concept in the calculation of all three parameters α, β, and γ, and that these aspects are all essential to realize a sustainable techno sphere, it is possible to define one “over all” parameter DOS, Distance to Overall Sustainability:

$$DOS \equiv \sqrt{\frac{(1-\alpha)^2}{3} + \frac{(1-\beta)^2}{3} + \frac{(1-\gamma)^2}{3}} \quad (5)$$

As is the case with all three parameters α, β, and γ, the DOS parameter varies between zero and one. However, there is an essential difference: when α, β, and γ are all one then DOS is zero. In this case the Distance to the Over all (α, β, and γ are all 1) Sustainability is 0, the system studied is completely sustainable from a technological point of view.

3.2.3 Application

In the first ten years of the 21^{st} century a comparison had to be made between two natural gas fed combined cycle (gas and steam turbine) power plants, combined with some kind of CO_2 abatement process (Zvolinschi et al. 2008). The first is a standard IEA power plant (Greenhouse R&D Programme, I. 2000), and, as a first step, the production of hydrogen by reforming of natural gas, and, as the second step, a hydrogen fed combined cycle power plant (e.g. Bolland et al. 2001 and Erstevåg 2005).

In this application we will focus on the first type of power plant considered. This power plant is a natural gas fired combined cycle plant without any emission abatement process. It is the process used for power production. In the second process this power plant is combined with CO_2 removal with a mono ethanolamine solution and conversion of CO_2 to biomass, anaerobic fermentation of the biomass, and finally PSA (Pressure Swing Adsorption) to produce methane and CO_2. In the third process the CO_2 removed from the flue gases is stored in a depleted gas reservoir. Later on in this paper we mention that the second process has to be combined with CO_2 storage (in the reservoir). This is because during periods of the year when no or not enough solar radiation is available CO_2 must be stored in a depleted gas reservoir, so that all CO_2 captured from the flue gases can be finally converted into methane and CO_2. All three power plants have a net electricity output of 400 MW. Table 1 gives relevant information about these processes.

Stream data	**Process 1**	**Process 2**	**Process 3**
Exergy in/[MW]	800.8	960.4	1136
$\dot{m}_{NG,in}$ /[kg/s]	18.22	21.85	25.85
$\dot{m}_{CO_2,EA,in}$ /[kg/s]	0	40.70	48.14
$\dot{m}_{H_2O,EA,in}$ /[kg/s]	0	0.010	0.012
$\dot{P}_{e,out}$ /[MW]	400	400	400

Table 1: Relevant data for the three natural gas fired power plants concerned.

In order to perform an exergy analysis, reference conditions must be determined. The reference temperature at the location in Norway is assumed to be 281 K, and the reference pressure is 0.101 MPa. The composition of air is given in mole fractions, and is chosen as: nitrogen x_{N2} = 0.7758, oxygen x_{O2} = 0.2082, argon x_{Ar} = 0.0093, carbon dioxide x_{CO2} = 0.0003, and water x_{H2O} = 0.0064. The seawater, used as cooling water, has a temperature of 281 K at a depth of 50 to 100 m. The temperature of this water is allowed to increase by 13 K.

The natural gas is obtained from a Norwegian offshore gas reservoir (North Sea) and is delivered at a pressure of 17 MPa and a temperature of 277 K. The composition of this natural gas, is given in mole fractions: methane x_{CH4} = 0.8394, ethane x_{C2H6} = 0.0487, propane x_{C3H8} = 0.0212, butane x_{C4H10} = 0.0077, pentane x_{C5H12} = 0.0023, hexane x_{C6H14} = 0.0007, carbon dioxide x_{CO2} = 0.0534, nitrogen x_{N2} = 0.0265, and water x_{H2O} = 0.0001.

All power plants have a net power output of 400 MW and their exergy efficiencies are respectively 0.50, 0.42, and 0.35 when for the second process the methane produced is not taken into account. CO_2 is removed from the flue gases by means of the Ecoamine FG process of Fluor Daniel, as described by Sander (1991). 90 % of the CO_2 is recovered from the flue gases with a final purity of 99 %.

CO_2 is stored in an exhausted gas reservoir in the North Sea nearby. CO_2 is first compressed in three stages with cooling after each stage to 293 K. In this way the pressure is increased to 6.0 MPa. In this state, CO_2 is a liquid and a further increase in pressure to 20 MPa is realized by a pump. The assumed reservoir conditions are: a depth of 1 km, a pressure of 14.5 MPa and a temperature of 333 K.

In Zvolinschi et al. (2008) a process is described to convert the captured CO_2 in ponds, on the sea surface, into biomass. This biomass consists mainly of micro-algae and is produced by photo synthesis. After concentration of the biomass, the biomass is anaerobically converted into a gas, mainly consisting of methane and CO_2, and a solid called digestat. The methane and CO_2 are separated by means of Pressure Swing Adsorption in a methane rich gas phase and a CO_2 rich gas phase. This process is schematically shown in Figure 2.

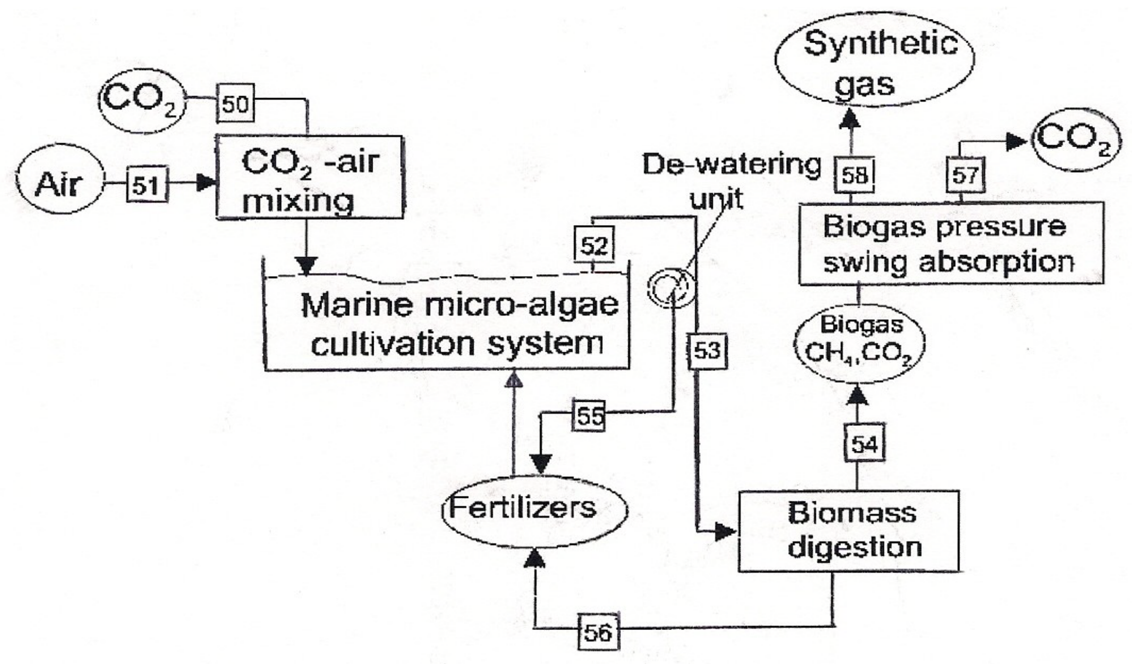

Figure 2: Overview of the micro-algae cultivation system in combination with anaerobic fermentation and gas separation to produce methane as fuel replacer for the power plant.

As shown in the figure 2, the "CO_2" stream (see table 1) captured from the flue gases (stream 50) is mixed with air (stream 51), the mixing ratio, on a mass basis, is 1:10, and, together with a fertilizer stream from the ellipse, indicated with Fertilizers, used as feed for the marine micro-algae cultivation system. A fertilizers make up stream is not indicated in figure 2. The produced marine micro-algae are pumped from this cultivation system (stream 52) to a de-watering unit. Here, a seawater rich stream (55) goes to the fertilizers system, and the bio mass rich stream (53) is fed to the anaerobic bio mass digestion system. The bio gas (mainly methane and carbon dioxide) from this system (stream 54) goes to a pressure swing adsorption unit where the gas is split in a methane rich stream (58), this gas contains 96 mole % of methane and has an assumed pressure of 2.0 MPa, and a carbon dioxide rich stream (57). The solids and liquid from the digester are returned to the fertilizer system (stream 56).

The marine micro-algae cultivation system consists of several 1000 ha ponds. Each pond is built up from 20 ha modules (Legrand, 1993). An average dry bio mass yield of 15 g/m^{2}day is assumed (Goldman 1979).

For the fixation of 90 % of CO_2 from the flue gases, a total marine surface area of 23400 ha is needed per year. In the Norwegian situation only in the months of April to September (during about half of the day) can biomass be produced in this way. The mean intensity of solar radiation at this place is 221 W/m^2. The total active surface area for micro-algae production is so large because in the photosynthetic active period all CO_2 removed from the flue gas stream is used in the ponds mainly during daylight. This is only possible when the power production process makes use of CO_2 storage in an exhausted gas reservoir during the night and in the months from October to March. The part of the solar radiation that can be used for photosynthesis is called Photosynthetic Active Radiation (PAR). A PAR value of 110 W/m^2 is assumed. Bisio et al. (1998) mention that 5% of the PAR is fixated as chemical exergy in biomass.

The following reaction was assumed for the conversion of CO_2 to biomass (Beker 1994).

$$106\ CO_2 + 236\ H_2O + 16\ NH^+ + HPO_4^{2-} \rightarrow C_{106}H_{181}O_{45}N_{16}P + 118\ O_2 + 171\ H_2O + 14\ H^+$$

The moisture content of the biomass is assumed as 90 wt%. The elemental composition of the dry and ash free biomass in wt% is: carbon: 52.4, hydrogen: 7.4, oxygen: 29.7, nitrogen: 9.2 and phosphorus: 1.3.

The de-watered biomass is fed in the digester, together with essential fertilizers to realize optimal growth of the bacteria able to convert the biomass to a gaseous mixture of, mainly, methane and carbon dioxide and a digestat. The digestat is recycled to the ponds but can also partly be used to improve the quality of soil.

An overview of the essential data for this process is given in table 2.

stream / power	$\dot{m}/[kg/s]$	$\dot{m}_{C,in}/[kg/s]$	$\dot{E}x_{in}/[MW]$	$\dot{m}_{C,out}/[kg/s]$	$\dot{E}x_{out}/[MW]$
$CO_{2,in}$	165	41.3	79.9		
Air_{in}	1650	0.2	0		
Exhaust gas	2740	4.4	31.8		
Solar radiation			92000		
$P_{de\text{-}watering\ unit}$			143		
$P_{digester}$			12.5		
P_{PSA}			67.7		
$CO_{2,out}$	33.2			7.1	14.9
$Methane_{out}$	33.2			23.7	1546
Total		45.9	92335	30.8	1561

Table 2: Essential data of the CO_2 abatement system finally producing a methane rich stream and a CO_2 rich stream by anaerobic fermentation of biomass consisting of micro-algae.

In table 2, we see that the total carbon input is 45.9 kg/s; the output of the methane and the CO_2 streams together gives 30.8 kg/s. Most of this difference can be explained by looking at the total fertilizer stream that is returned to the ponds. This stream contains 10.5 kg/s

The exergy efficiency η of this methane production process is defined as the ratio of the sum of the exergy values of all useful products and the sum of all exergy inputs. From table 2 we can determine this exergy efficiency, η = 0.017. The outgoing CO_2 stream, still containing methane, can be used as carbon source for the ponds when the methane in this stream is converted into CO_2, and the methane stream can partly replace natural gas, thus the natural gas input of the power plant can be reduced.

This option to generate part of the methane by the process described is not suitable to close the carbon cycle in the techno sphere because of the negative effects of the use of the ponds on sea life. These are related to the boundary condition to make use of solar radiation in such a way that the optical characteristics of the surface remain the same as before making use of the solar radiation. Furthermore, 10 wt% of the CO_2 is still left in the treated flue gases. Further treatment with (wet) calcium oxide, binding CO_2 much stronger than with ethanol amines, to further reduce the CO_2 content of the flue gases is possible. A consequence is the much larger exergy input for this process than for the ethanol amines based processes.

In comparison, between two alternatives to produce mainly ethanol starting with the exergy input of solar radiation, the alternative via biomass has a lower exergy efficiency than the other more “chemical” route – see Dewulf et al. (2000) and Mulder et al. (2000). This chemical route starts with electricity production using microcrystalline silicon PV cells. The production of these PV cells has a large environmental impact. The exergy efficiency of electricity production is 0.126. The next step is the electrochemical production of hydrogen and oxygen by electrolysis of water. Oxygen provides the possibility to perform oxidation processes in our techno sphere, comparable to its role in living systems. Hydrogen can be used in general for reduction processes in the techno sphere, comparable to NADH, H bonded to a large organic molecule, in living systems. The exergy efficiency of this process is 0.68. CO_2 is obtained from the flue gases of a coal-fired power plant with an exergy efficiency of 0.079. When carbon from fossil origin is used in the techno sphere it can (finally) be converted to CO_2 by oxidation, for example to produce thermal energy and electricity in this last conversion step.

This CO_2 can be reduced (by hydrogen) to produce substances that must be used in our techno sphere, taking care of the boundary conditions mentioned before. The CO_2 can be converted to methane by making use of hydrogen as the reducing agent (Inui et al. (1998) and Barbarossa et al. (2009). Such a process, for large-scale production of methane, is not available on the market and has to be developed further. Based on the analysis of Mulder et al. (2000), we can assume an exergy efficiency of 0.75. The exergy efficiency for this over all production process of ethanol or methane is nearly the same: 0.082. Although, the exergy necessary for the abatement processes related to the production, use and product abatement has to be taken into account, as is also the case with the construction, use, and demolition phase of the production facilities and other related exergy inputs, to determine the total amount of exergy needed for all abatement processes to produce and use methane, for simplicity reasons we will assume that only the exergy input for the production chain of methane discussed will be considered as representative for the emission abatement processes.

The total exergy input to produce 1 mole/s of methane at standard conditions (pure gas, P_0 = 0.101 MPa and T_0 = 298.15 K) is 3.96 MW via the “chemical” route. As said, this can be considered as an approximation of the amount of exergy necessary to abate the CO_2 emission from a natural gas fired power plant in the techno sphere. We can now determine the parameters α, β, and γ for the natural gas fired power plant not combined with any CO_2 abatement process. For this process the renewability parameter $\alpha = 0$ because no renewable input is used. The efficiency is $\beta = 0.500$ for the power plant without CO_2 capturing. The electricity output per mole/s of methane can be obtained from the chemical exergy of methane at the standard conditions mentioned before, this is 832 kW/mol, times β. The electricity output per mole/s of methane is then 416 kW (or 0.416 MW). The emission abatement parameter γ must be calculated from the quotient of the exergy value of the electricity produced, 0.416 MW, and the total amount of exergy necessary for the abatement processes in the techno sphere, 3.96 MW. In this case the contributions from resource extraction and the process facilities per mole of methane can be neglected as a consequence of the large capacity of the reservoir and the lifetime of the process facilities, in this case in the order of 30 years. This gives $\gamma = 0.095$. The Distance to Overall Sustainability, on a scale from 0 to 1, is then:

$$DOS = \sqrt{\frac{(1-0)^2}{3} + \frac{(1-0.500)^2}{3} + \frac{(1-0.095)^2}{3}} = 0.830 \tag{6}$$

We see that we still have to do our utmost best to reduce this value much more substantially to realize a DOS parameter value close to 0.

An other interesting point to note is that the amount of exergy necessary in order to use methane in a sustainable way in the techno sphere is 3.96/0.832 = 4.8 times as large as the chemical exergy value of methane/mole. When we take this into account, it becomes apparent that it is not very wise to use fossil methane and that the cost of methane should be 4.8 times higher than we are now used to, based on exergy as a weighting factor.

From what we have seen before, we can now define a new parameter δ that is related to the abatement of emissions only. When we have defined a route to abate emissions related to the use of a certain substance (e.g. methane) in our techno sphere, making use of existing processes and (eventually, when necessary) also of processes still in the development phase, we can calculate the total exergy input for this route. This amount of exergy is then a measure for what we must do to make the process sustainable. δ is defined as:

$$\delta \equiv \frac{Ex_{real}}{Ex_{route}} \qquad (7)$$

Ex_{route} is the total amount of exergy input for the route defined to abate the emissions, and Ex_{real} is the amount of exergy input for the process(es) used for partial abatement. Examples of partial abatement processes are the processes described in this paper to capture CO_2 from the flue gas stream, to use this to grow algae, to anaerobically digest the biomass to mainly produce a mixture of methane and CO_2, and to separate them by pressure swing adsorption (PSA). From the data given in tables 1 and 2 we can calculate δ = 0.245/3.96 = 0.062.

δ must be used in combination with another parameter ε, because in principle δ can have a value larger than 1 when very bad abatement processes are used. ε expresses, in an other way than δ, what we have achieved concerning recycling substances that can be used as input for our processes in the techno sphere. In the case we are considering, we recycle CO_2 in the form of methane (mainly produced by exergy input from solar radiation) to partly replace the natural gas input of the power plant. In this case we can define ε as the quotient of the number of moles/s of methane recycled and the number of moles/s of methane (considered as the exergy-equivalent of the moles/s of methane with the input of natural gas):

$$\varepsilon \equiv \frac{n_{CH_4,recycled}}{n_{CH_4-equivalent,input}} \qquad (8)$$

$\dot{n}_{CH_4-equivalent,input}$ is calculated from the exergy value of the natural gas input, 1136 MW, divided by the chemical exergy value of 1 mole of methane, 0.832 MJ/mole. Thus $\dot{n}_{CH_4-equivalent,input}$ = 1365 moles/s methane. The average value of the number of moles/s over one year is 137.4 moles/s methane. This value can be easily calculated from de the data in table 2 for one quarter of the year daylight (the ponds are used during half of the year and half of the day sunlight is available). From these data we obtain: ε = 0.10. When we compare this ε value with the δ value determined before, we can see that 0.1 of the methane is recycled at a relatively small exergetic cost. However, as stated earlier, this abatement option does not comply with the boundary condition to maintain and possibly enhance biodiversity.

3.2.4 Conclusions

Based on the information given, it was possible to define a renewability parameter α, an efficiency parameter β for the process considered, and an emission abatement parameter γ. These parameters can vary between 0 and 1, 0 being very bad and 1 being the best case. These parameters can be combined in one overall parameter called DOS, the distance to overall sustainability, also varying between 1 and 0. However, for this parameter 1 is very bad and 0 indicates a sustainable activity in the techno sphere.

These parameters were determined for a natural gas fired combined cycle power plant without any flue gas treatment. For this case α = 0 because no renewable exergy is used, β = 0.500, and γ = 0.095. The related DOS value is then: DOS = 0.830. This indicates that we are still far away from a sustainable electricity production system when making use of a natural gas fired power station. It is not so easy to determine the parameter γ, because we have to think about processes by means of which the emissions can be abated in such a way that only emissions to the ecosphere are allowed. Additionally, such emissions should only be allowed for substances that: can be recycled to the ecosphere; do not overburden the natural cycles; play a part in maintaining soil quality and; preferably contribute to an increase of bio diversity. Furthermore, substances such as those making up the composition of the soil and the different types of soil themselves can be returned to the ecosphere with proper care. All other products must be recycled in the techno sphere, when necessary, after treatment, as substances that can be used as feed for our production processes. In the case considered, methane is produced from hydrogen and CO_2. PV cells produce electricity and this is used to electrolyse water to produce hydrogen (a reducing agent) and oxygen (an oxidizing agent). This oxygen can finally convert carbon in the techno sphere into CO_2.

A process is described where CO_2 captured from fossil fuel based flue gases is used in ponds to produce micro algae and to convert them via anaerobic fermentation in a digestat and a gas mixture mainly consisting of methane and CO_2. Finally, this gas mixture is separated by means of PSA into methane and a CO_2 rich gas streams. This methane can replace, partially, natural gas to produce electric power. This process made clear that it was useful to define still two other parameters to value actual emission abatement processes. The parameter δ is defined as the exergy input used in the actual emission abatement process considered, compared to the total amount of exergy necessary to completely abate this emission in a sustainable way. For the micro algae system δ = 0.062. This δ can have a value larger than 1 in the case that a very bad abatement process is evaluated. This is the reason why also another parameter ε is defined. This parameter is the quotient of the number of moles/s of substances produced that can be used as input for process via the abatement process considered and the number of moles/s of these substances actually used as feed for the process. In the case considered the exergy/s value of the natural gas is divided by the exergy value of 1 mole of methane to obtain the number of moles/s of methane equivalent to the total exergy input of natural gas. For the case considered ε = 0.10. When we compare this ε value with the δ value, we can see that 0.1 of the methane is recycled at a relatively small exergetic cost.

The context in which the parameters have been defined makes the technological component of sustainability much more tangible and assessable and can be of help to guide us on the route to a sustainable techno sphere. This makes it possible to develop technology and related research necessary to continue our journey to a sustainable technological future appropriately.

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3.3 An Exergetic Analysis and Potential for Improving the Rational Energy Use in Dwellings

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3.3.1 Introduction

Traditionally, when referring to usual processes in household buildings, the main parameter considered is the energy consumption – see, for instance, the energy labeling concept (Mahlia et al., 2002). From a thermodynamic perspective this is only partially correct: considering the energetic efficiency in a boiler might lead to rather good results, but would these figures really describe the “actual” efficiency?

The idea of exergy may be useful to answer this question: exergy is a function that takes into account both the first and the second law of thermodynamics. The most general formulation of the exergy equation will be now written (Mahlia et al., 2002) for an open system as a room, considering the exergy associated to heat and mass transfer and neglecting other components of exergy transfer, such as kinetic and potential exergy; under steady state assumption, the first law of thermodynamics can be written as:

$$E_{in} = E_{out} \tag{1}$$

On the other hand, according to the second law of thermodynamics, the entropy production in the above mentioned system is:

$$S_{in} + S_{gen} = S_{out} \tag{2}$$

Where S_{gen} = 0 only in a reversible process.

By multiplying equation (2*)* with the reference temperature T_0 and subtracting it from equation (1) results in:

$$(E_{in} - S_{in}T_0) - S_{gen}T_0 = (E_{out} - S_{out}T_0) \tag{3}$$

That is: (Energy input –Anergy input)-Anergy generated = (Energy output – Anergy output)

$$Ex_{in} - Ex_{consumed} = Ex_{out} \tag{4}$$

Anergy is the product of the entropy related to an energy flow and its environment temperature: it is the part of the energy flow that cannot be converted into work. By subtracting this amount from the energy flow, the exergy flow is obtained, i.e. the valuable quantity of the energy that can entirely be converted into work.

Equation (4) is a general equation for the exergy balance: Ex_{out} is the maximum amount of exergy that can be obtained from a system whose supplying exergy is Ex_{in}: the smaller the exergy consumed, the smaller the exergy loss.

In buildings, since Ex_{out} is "fixed" by the overall need to heat the building and to feed its appliances, the aim is to reduce the Ex_{in} in order to lower the $Ex_{consumed}$. Most of the traditional systems, in fact, use energy sources with high exergy content. A boiler can easily reach thermal efficiency values over 90% or even greater with condensing boilers, but its exergy efficiency is much lower (Mahlia et al., 2002; Schmidt, 2004). The low exergy efficiency values here are the "mathematic" translation of what the second law of thermodynamic states: in a boiler, different processes take place: first the conversion from a more valuable form of energy, the fuel chemical energy, to the lower exergy of the high temperature gases. Secondly, heat is exchanged with a lower temperature fluid and a second and bigger thermodynamic loss takes place. Even assuming that the conversion of chemical exergy to heat exergy is virtually free of energy losses (i.e. no heat given to exhaust gases and no heat dispersions toward the external environment) there is still an exergy loss, due to the bad matching between a high exergy source and a low exergy output: the difference between input and the output in the system is irreversibly lost. It is therefore mandatory to review the different outputs, i.e. the energy levels, in the most common household energy processes, to quantify the exergy, i.e. the energy quality, in the processes considered and to understand how rationally the energy is used.

Common energy sources in dwellings are fossil fuels: it would be possible to redirect the high exergy sources where they are really needed (for instance the production of electricity) and to supply the low exergy needs with low exergy sources (usually low-cost, renewable ones). In this way it would be virtually possible to shift most of the high exergy sources from building-related processes, usually with very low exergy needs, to other energy fields. If we assume that the whole household energy needs are covered by renewable sources (solar panels for instance), part of the exergy consumption could be saved. In addition, there would be technical problems and it would be necessary to create markets. None the less, this might be a relatively feasible way of saving energy and have positive implications on the development of future markets.

3.3.2 Analysis of household exergy needs

As a first step, an exergy-need analysis of the most common processes is done by determining an exergy factor value for each process. This factor is the ratio between exergy and energy flowing into the considered system (e.g. a household). The aim is to find out what the exergetic level of every process is: rather than exergy consumption in absolute terms, the aim is to obtain an order of magnitude of the energy quality involved in the processes. Space heating at 40°C has a much lower exergy level than an oven running at 250°C, as exergy factors clearly show.

Many appliances are involved in the consumption of hot water and mechanical energy. The pumps for instance: in this case the exergy is referred to the main energy flow, neglecting the smaller energy uses. Another example is an oven: there are commonly electrical devices such as fans, lights and thermostats that consume an amount of energy much smaller than the one used to cook: therefore they have not been taken into account.

The thermal exergy values have been obtained by multiplying the exergy factor F_Q by the thermal energy Q:

$$F_Q = 1 - \frac{T_0}{T} \tag{5}$$

T_0 is the reference temperature and T is the temperature in the considered process. With regard to T_0, 15°C, the yearly average temperature on Earth, has been chosen for every process due to the general perspective of this paper. The thermal exergy is therefore:

$$Ex_Q = Q \times \left| 1 - \frac{T_0}{T} \right| \tag{6}$$

Process	Typical Temperatures [°C]	Typical Temperatures [K]	Exergy Factor [ ]
Freezing	-20	253	0.138
Refrigerator	4	277	0.040
Air Cooling	10	283	0.018
Floor Cooling	12	285	0.011
Reference level	15	288	0
Air heating	26	299	0.037
Floor heating	35	308	0.065
Shower/bathing	40	313	0.080
Hair-drying	55	328	0.122
Dish washing	60	333	0.135
Laundry-drying	60	333	0.135
Radiator heating	70	343	0.160
Washing	70	343	0.160
Boiling	100	373	0.228
Frying	200	473	0.391
Ironing	210	483	0.404
Baking	250	523	0.449

Table 1: Typical processes in dwellings and related exergy factors

Table 1 shows the exergy factors for heating/cooling activities taking place in buildings. The exergy factors are equal to the Carnot factors in these cases

Figure 1 shows how small the exergy needs in a house are. This becomes of great importance when considering that most of these processes are supplied with high exergy sources. Fossil fuels, whose chemical exergy factor is close to 1, are commonly used for space heating – in boilers - and electricity is often used for most of the other processes. For hair-drying up to and including baking with exception of, eventually, radiator heating high quality exergy sources such as electricity and natural gas are used for low quality purposes.

An exergy efficiency can be introduced as ratio between the desired output, i.e. the exergy output of the process, and the supplied input to feed the considered process.

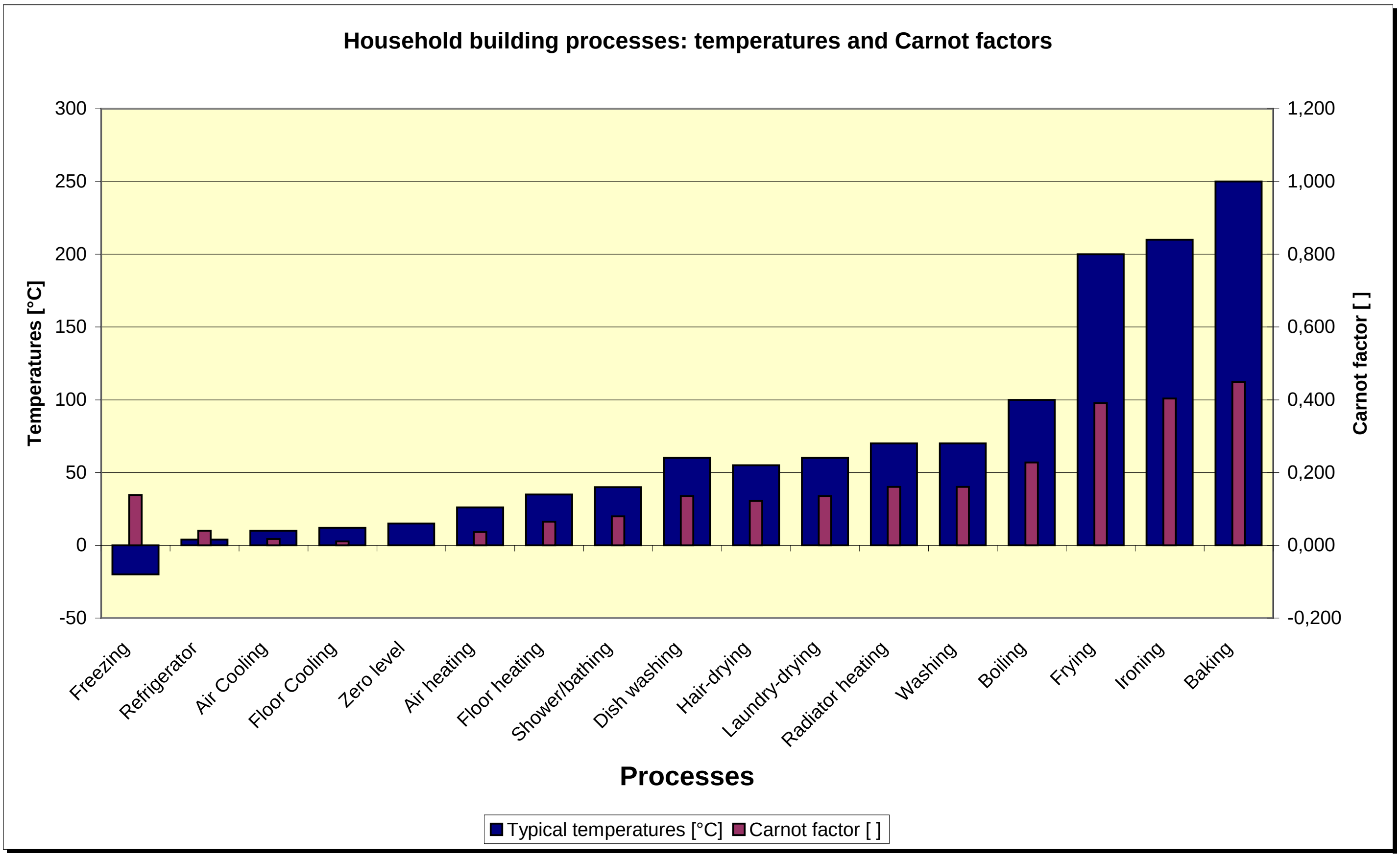

Figure 1: Usual processes in a dwelling: exergy levels and temperatures

It is clear how thermodynamically inefficient, or irrational, the energy usage in households is. This is due to the use of high exergy electricity, which is easy to transport and to use, flexible, and relatively cheap to produce. On the other hand, the potential for energy saving is impressive: this high quality energy could be shifted to where it is really necessary, i.e. where work needs to be done by the exploitation of pure exergy: a great amount of primary energy could therefore be saved. The energy use in buildings, in fact, accounts for about one third of the total yearly energy consumption in the world, with rather small differences in the Western countries.

3.3.3 Three examples

Among the considered processes, three of them have been chosen for further analysis:

1. Dishwashing, as an example of relatively low temperature heat needs for appliances
2. Refrigerator, as a representative of cooling needs
3. Space heating, as an example of space conditioning

Dishwashing

The first example is the working of a dishwasher. According to the European Energy labeling, the energy consumption for each cycle typically varies from about 1 kWh to 2 kWh, depending on the class. Most of the energetic consumption, roughly 80%, goes toward heating water, the rest being used in drying and water pumping. In this example, the hot water temperature is set at 60°C. 0.8 kWh of the energy, supplied by electricity, is consumed by a class "A" piece of equipment; assuming a reference temperature of 15 °C results in 0.1 kWh exergy. As will be shown below (Eq. 7), this results in an exergy efficiency of 0.125, or 0.13 for simplicity.

What is the use of this result? Indeed, it does not mean that the amount of energy that is actually needed is 100 Wh, but it gives useful information on how rationally the exergy input is used. It is actually required to satisfy both of the needs, but it must be stressed that this process allows us to use other kinds of energy that can be supplied otherwise and that would not be profitable in a power plant producing electricity: the issue at hand is how to use this "thermodynamic opportunity".

In this case a possible alternative is to use freely available energy from the sun, by using a solar collector coupled with a storage system to have energy available even on cloudy days. A supply temperature of 70 degrees can thus be reached.

A measure of the improvement of the matching between the different forms of energy is calculated by dividing the Carnot factor of the two input and output energy flows and assuming that the energy losses are negligible, so that:

$$\eta_{EX} = \frac{EX_{out}}{EX_{in}} = \frac{1-\dfrac{T_{ref}}{T_{need}}}{1-\dfrac{T_{ref}}{T_{\sup ply}}} = \frac{1-\dfrac{15+273}{60+273}}{1-\dfrac{15+273}{70+273}} = 0.84 \tag{7}$$

The exergy efficiency before improvement was around 0.13, which indicates bad matching between the source and the actual exergy need. In the improved solution, the efficiency is 0.84, which is closer to 1. Two effects result: a decrease of the exergy waste and the exploitation of freely available solar energy. This is not always possible, as the next example will show.

Refrigerator

A simple refrigerator unit is assumed to be made up of four elements: an evaporator, a compressor, a condensing unit and an expansion unit (usually a throttling process). The system scheme is drawn in figure 2:

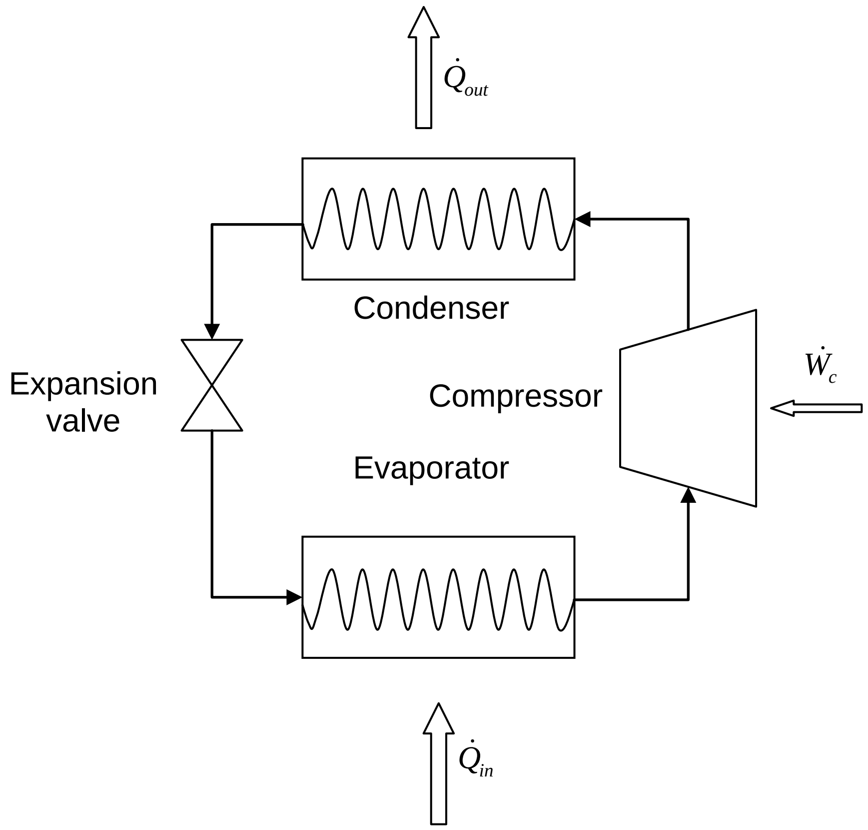

Figure 2: Components of a vapor compression refrigeration system.

Typically, the saturated vapour at the evaporator outlet is at a temperature of about 0°C to draw heat from the cold ambient at 4°C, while the temperature at the condenser can reach the value of 50°C, assuming an outside temperature of 20°C.

The exergy factor is 0.04, the reference temperature being 15°C. This exergy factor has the same value as the exergy efficiency, assuming an electric supply with an exergy factor of 1. In this case as well there is a great potential for exergy saving: more than 95% of the exergy supplied is destroyed: however, there is not a technical solution as easy as in the previous case. Cooling loads are less easy than heating loads to be rationally satisfied from an exergetic point of view: while it is possible to obtain “free” warm exergy from the sun, it is much more difficult to obtain low temperatures cooling flows for free: the use of heat pumps supplied with hi-quality energy is therefore needed.

A possible alternative could be the use of a “cold storage” that could supply directly the storage space of the refrigerator. The “cold source” can be charged during the night time, taking advantage of the lower temperatures. This system however would not accumulate “cooling energy” with temperatures low enough to supply the system directly and the “cold source” cannot be charged during the whole year/part of the day.[1]

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[1] Another thing to be considered is the refrigeration system itself. Electricity is used to drive the compressor and to provide exergy to the cooled space and the environment, although, the exergy increase of the environment can be reduced to nearly zero by appropriate design, and where also the exergy losses in compressor, evaporator, and expansion valve are small, nearly all electricity input is used to provide exergy to the cooled space. Thus, refrigeration systems (and heat pumps in general) can in principle be very exergy efficient, if properly designed. [addition by the editor]

Space heating

The case considered in this third example is a low temperature (35°C) floor heating. Similar to the first case study, the exergy factor, seen as ratio between exergy and energy, is rather low, 0.064. Energy is supplied by the use of a boiler: the fuel (gas, diesel) energy content is converted into heat and transferred to the floor heating, with a given energy efficiency.

Here too, the value of the supplied exergy is much lower than the chemical exergy, assuming, as suggested for instance in Mahlia et al. (2002), an exergy factor of 0.9. As a result, the exergy efficiency would be 0.071, quite low.

A possible solution to improve the exergy efficiency can be the use of solar collectors. In this case another kind of problem has to be overcome: the technical feasibility of this solution depends on the required energy amount. The heat energy need of a dwelling of 150 m^2, with an U-value for external walls of 0.2 W/(m^2 K), can reach the order of magnitude of hundreds of kWh for a week in a continental climate location (Noguera Casselles, 2007). That amount has to be supplied by a backup system, and/or be retrieved from an energy storage system in case of lack of solar radiation.

3.3.4 Conclusions

This section dealt with a general analysis which focused on exergy consumption of processes that take place in a household. Exergy and exergy efficiency were used as parameters for assessing the rational use of energy in three cases.

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3.4 Do prices for energy carriers reflect their exergy content?

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3.4.1 Introduction

A large variety of technologies exists for providing space heating and hot water. Although there is a considerable difference in traditions of heating systems in various regions, we can observe that historically the mix of fuels changed from biomass towards oil, gas and coal during industrialization. At the same time, efficiency and emission standards of heating systems as well as comfort levels increased strongly (IEA, 2004). In addition, modern heating solutions include systems like solar heating, heat-pumps and, in general, an improved energy economy of buildings through better insulation, air-tightness and other energy-efficiency measures (e.g. Ala-Juusela and Rautakivi, 2003, Entrop et al., 2010).

All these heating systems show different specifications and impacts, e.g. in terms of economic characteristics. In particular, such characteristics refer also to the share of various cost components, i.e. the cost structure regarding capital costs, operating costs and energy costs. The energy costs of energy carriers can differ considerably, as can the quality of energy carriers and energy services. One of the core indicators measuring the quality of an energy carrier is its exergy content. One could assume that people, when buying energy, are interested in the portion of the energy capable of performing work for them, namely exergy, rather than unusable forms of energy. Therefore, one of the hypotheses in this study is that, in a theoretical concept of a well-functioning energy market with ample choices, and no market distortions, transaction costs etc. the price of an energy carrier reflects its exergy content rather than energy content. Thus it can be expected, that low-exergy energy carriers (e.g. low-enthalpy heat) have a lower price level than high-exergy carriers (e.g. electricity or natural gas). However, for a given end use such as heating, the total cost of the energy carrier and capital investments necessary to provide the energy service should be about the same for all systems, at least in case that the systems provide a similar comfort level and market distortions are negligible. Based on these premises, one could state the following hypotheses:

- the prices of well-established energy carriers in the marketplace reflect exergy content;
- the total heat generation costs for widely used systems are generally on an equal level within a country or region regardless of the energy carrier;
- there is a tradeoff between capital input (i.e. high investments for technologies) and exergy content of applied energy carriers. In other words, the lower the exergy content, the higher is the capital requirement finally leveling out at least some part of the lower energy costs for the low-exergy energy carriers.

The objective of this section is to investigate to which extent it is possible to verify these hypotheses, with a particular focus on the last hypothesis. Hence, this section aims at exploring, for a set of given conditions:

- to what extent the prices for different energy carriers in fact represent their exergy content;
- to what extent there is a tradeoff between capital input and exergy content of applied energy carriers for different heating systems.

Our analysis uses data from selected European countries: Austria, Finland, the Netherlands, and Sweden. These countries show large similarities regarding the physical quality of buildings, energy consumption per capita, gross domestic product per capita, and VAT-rates. On the other hand there are differences in climate, heating system traditions and building stock. In view of the above-mentioned objectives, data for these countries can be seen to provide a robust base for a first comparative analysis.

3.4.2 Methodology and applied exergy content

This section provides a short overview on our methodology, the definition of monetary heat generation costs and applied exergy content.

Approach and limitations
Our approach consists of the following steps, which are carried out for each country covered in this paper (AT, FI, NL, SE):

- define a characteristic building type along with several heating systems using different energy carriers to be compared in the analysis;
- investigate the different cost components of heating systems. These are investment, operation and maintenance costs for different heating systems and their components. Variable energy costs on the other hand are represented by the price which consumers pay for a given fuel or energy carrier. In particular, we distinguish between net energy prices and energy taxes;
- define the exergy factor for each of the energy carriers considered;
- compare the exergy factor to the energy price (with and without taxes) for each energy carrier;
- compare the specific exergy content (exergy factor) to the total monetary cost of heat generation for various heating systems. The total monetary cost of heat generation in this paper is defined as the sum of monetary expenses that a residential consumer has to pay for providing and maintaining a comfortable amount and quality of thermal energy to a dwelling. This includes energy prices (excluding taxes), energy taxes and total fixed costs (investment costs, operation and maintenance costs);
- finally, we calculate the share of variable energy costs on total heat generation costs for different heating systems and relate this indicator to the specific exergy content (exergy factor) of applied energy carriers. This indicator (share of variable energy costs on total heating generation costs) shows the cost structure of the heating system: the higher this share-value, the lower the investment costs (capital requirement) compared to the energy costs. Thus, a low value of this indicator means, that an expensive technology is applied, making use of cheap energy carriers. Comparing this indicator to the `specific exergy content (exergy factor) applied, leads to insights to which extent

there is a tradeoff between high investment requirements for making use of low exergy energy carriers.

This approach, we believe, leads to new and interesting insights about the extent to which current energy market prices take into account the exergy content of energy carriers. In doing so, we considered some critical aspects to this approach, as outlined below:

- given the differences in climate, housing stock, adopted technologies and economic conditions, the comparison of different countries is not straightforward;
- taxes on energy carriers are different in each country and have considerable impact on the outcome of our analysis. Therefore, prices with and without energy taxes are distinguished;
- energy prices have shown considerable volatility within the last few years. While price volatility has not been the same for all energy carriers, the level of energy prices strongly affects the ratio of capital to energy costs. We use energy price levels of the year 2005 in all investigated case studies in order not to reflect the strong price volatility of the years 2007 and 2009. However, we are aware that the reference year for energy prices has crucial impact as a parameter.
  Further research could add sensitivity analyses with respect to different energy price levels, and apply the concept for various prices according to future energy price scenarios ;
- besides energy taxes, other instruments of energy policy have an impact on the economic performance and characteristics of heating systems. This includes investment subsidies and regulations, in particular with respect to district heating etc. We do not focus on these aspects in this work and leave this for further research.

Definition of monetary heat generation costs

A wide variety of literature exists in the context of exergoeconomics, exergetic costs, exergy accounting etc.(e.g. Tribus and Evans, 1962; Lozano and Valero, 1993), (Tsatsaronis and Moran, 1997; Valero et al., 2006; Deng et al., 2008; (Sciubba et al., 2008).

In contrast to most of this literature, in this paper the term “costs” is related to monetary costs rather than exergetic, physical costs (e.g. Valero et al., 2006). These monetary costs refer to the monetary expenses an energy consumer has to bear for a certain type of heating system. This includes investment costs, operation and maintenance costs and energy costs. The latter ones are dependent on the energy price and the efficiency of the heating system. Typically, for grid connected energy carriers a considerable part of the energy price consists of a base price, which is independent of the actual energy consumption. This base price can be understood as element to take into account the up-front investments in the district heating grid etc. Due to our system boundary being the building envelope, we do not consider this in an explicit manner.

We distinguish between the terms “price” and “cost”. Energy prices are the result of supply and demand intersections on energy and resource markets. Thus, they reflect the relation of supply and demand for different energy carriers. Heating related energy costs are the expenses that consumers have to pay for a heating system. This includes fixed costs (investments, operation and maintenance), energy taxes and costs for energy carriers. The latter are represented by energy prices (in a market driven economy) and energy taxes.

The following financial flows are distinguished (see equations 1-4):

- variable price for energy carrier C_{en} [€/MWh] excluding tax;
- energy related taxes $C_{en,tax}$ [€/MWh] based on the energy tax rate ($f_{tax,en}$) of this specific energy carrier;
- total fixed costs, consist of:
  - leveled investment costs of the heating system I_{hs} (€), using the capital recovery factor α. For calculation of the leveled investment costs we used an interest rate (i) of 5% and a depreciation time (T) of 15 years;
  - annual operating and maintenance costs $c_{O\&M}$ (€/yr), and the annual fixed amounts paid $c_{en,fix}$ to the energy supply company regardless of the actual energy consumption;

$$c_{tot} = (C_{en} + C_{en,tax}) * e_{en,f} + c_{fix} \left[\frac{€}{yr}\right] \tag{1}$$

$$c_{en,tax} = c_{en} \cdot f_{tax,en} \left[\frac{€}{MWh}\right] \tag{2}$$

$$c_{fix} = c_{O\&M} + c_{en,fix} + \alpha I_{hs} \left[\frac{€}{yr}\right] \tag{3}$$

$$\alpha = \frac{(1+i)^T - 1}{(1+i)^T \cdot i} \left[yr^{-1}\right] \tag{4}$$

$e_{en,f}$ is the total amount of energy necessary during one year [MWh/yr].

All financial parameters are calculated without value added tax (VAT). As VAT is always placed on top, it only influences the overall price level of a country, yet has no impact on price comparisons within a country. The relevant VAT rates in the analyzed countries (Austria, Finland, the Netherlands, and Sweden) are 20%±1% (2010).

Subsidies and other promotion schemes also have an impact on the competitiveness and total heat generation costs of different heating systems. In our analysis they could have analogous effects to energy taxes. In order to focus on the key issues the impact of subsidies was not taken into account in this research. Multiple national institutions provided financial data regarding energy prices and economic variables. E.g. (Müller et al., 2009), (RES, 2009), (Regionalenergie Steiermark, 2010). (Finnish Energy Industries, 2006), (Statistics Finland, 2007), (Statistics Finland, 2009), (Motiva, 2007), (CBS, 2009) (Energiekamer, 2005). (Statistiska centralbyrån, 2007a), (Statistiska centralbyrån, 2007b).

The total costs are calculated based on the data presented in the Annex in tables 2-5 for Austria, Finland, the Netherlands, and Sweden respectively.

Applied exergy content

Chemical energy is a much-used basis for primary energy conversion, often through combustion. The temperature levels that can be reached in such combustion processes, determine the amount of the chemical exergy that in practice can be converted into thermal exergy. In other words, in combustion processes there is always a certain amount of unavoidable exergy loss due to the limited maximum achievable temperature levels. The exergetic efficiency, combustion of an ideal combustion process is determined by the second law of thermodynamics, and depends on the absolute temperature levels of combustion and of the environment. Thus, the maximum achievable exergetic efficiency of a combustion process indicates the amount of “in practice maximum usable” exergy (i.e. total exergy content minus unavoidable exergy losses).

Table 1 shows the resulting specific exergy content (exergy factor) of the energy carriers analyzed in this paper. Further explanations are included in (Kranzl and Müller, 2010) and (Müller et al., 2010).

Energy carrier (temperature level)	Temperature level	Reference temperature level	Exergy content as used in this paper
Oil, coal, gas	1500 °C	0°C	85%
Biomass	800°C	0°C	75%
Electricity	-	-	100%
District heat inlet flow	100°C	0°C	27%

Table 1: Specific exergy content (exergy factor) of the energy carriers analyzed in this paper

3.4.3 Results

This section summarizes the results of our analysis. Figures 1 and 2 show the fuel costs (excl. and incl. energy taxes, respectively) for the investigated heating systems in each of the countries in relation to the exergy factor of each system’s energy input.

The graphs indicate that in general heating systems making use of high exergy forms (electricity, oil, gas) show higher energy costs due to the higher energy prices, and also partly due to the higher energy taxation. However, there are also exceptions which should be thoroughly discussed. (1) The household’s variable energy costs for district heating in the Netherlands and Sweden is relatively high compared to the low exergy content of district heating. There are two major reasons for that. On the one hand, the share of variable energy costs of district heating is first of all a matter of tariff structure. This structure is usually strongly influenced by (local) energy policies. Moreover, the overall price level of district heating in many countries is subject to energy policy decisions. E.g. in the Netherlands there are regulations regarding district heating prices which refer to the heat generation costs of competing heating systems (natural gas). (2) Biomass in general shows relatively low fuel costs in relation to its exergy content. Here, we have to take into account that solid fuels have very different characteristics compared to liquid, gaseous and electric energy. Thus, there are additional specifications and quality indicators of energy carriers besides their exergy content.

Taking into account these specific aspects of district heating and biomass, we can conclude that in general heating systems using high exergy forms of energy show higher energy costs, in particular if energy taxes are included.

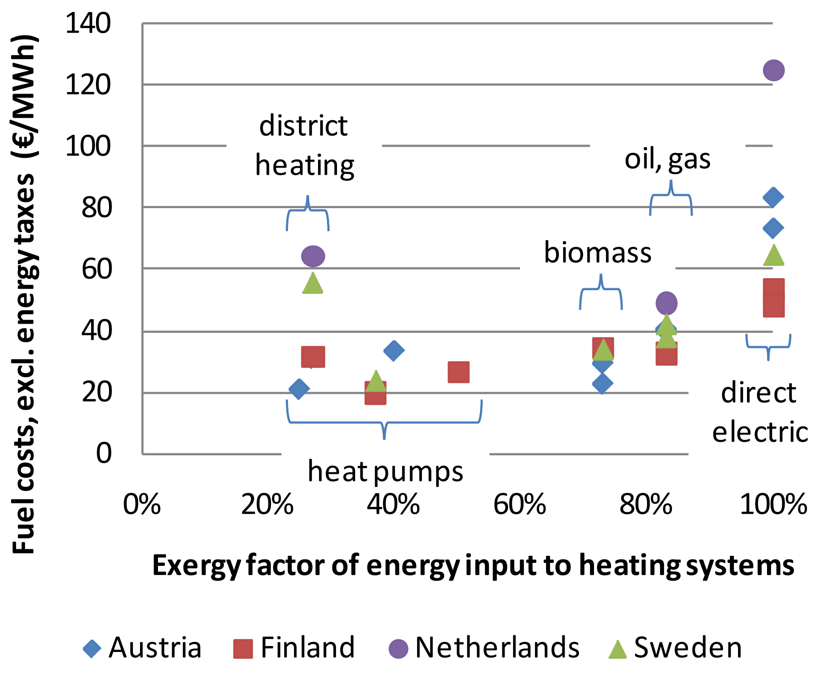

Figure 1. Fuel costs (excl. energy taxes) and exergy factor for various heating systems

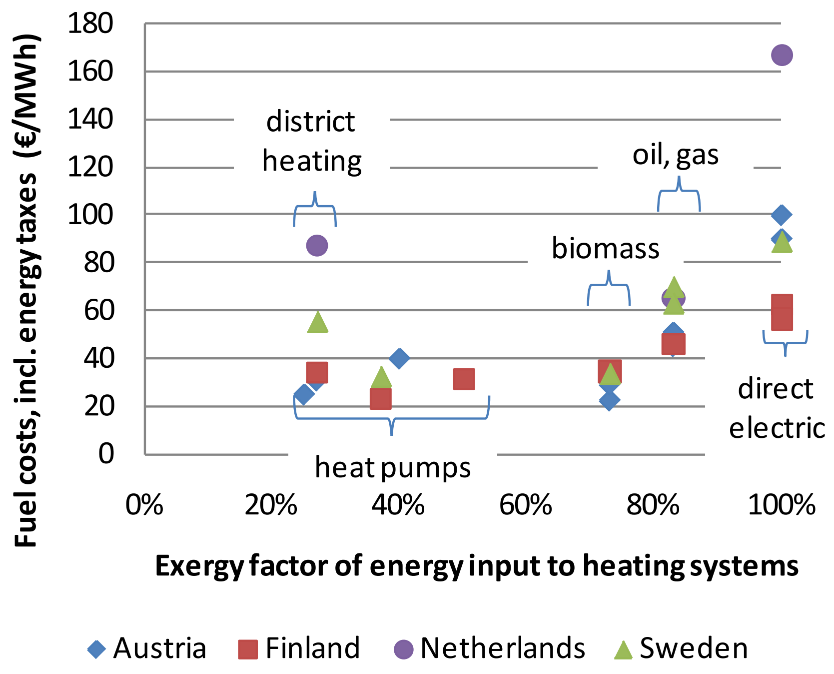

Figure 2. Fuel costs (incl. energy taxes) and exergy factor for various heating systems

Below, we calculate the share of variable energy costs of the total heat generation costs for each technology and country (each including energy taxes) for each heating system. A low share of variable energy costs indicates that a relatively high share of the total heat generation costs is due to investment costs. A high share means that only a relatively low amount of investments is necessary to provide useful heat with this heating system.

Figure 3 summarizes the results of this analysis: it shows a rather strong relation between the share of variable energy costs (mainly influenced by energy prices, taxation of energy carriers and the efficiency of the heating system) and the total heat generation costs and the exergy factor of the used energy carriers for many data points. This shows that the lower the exergy factor, the higher the investment and capital needs for making use of this low-exergy energy source. Major outliers can be explained by taking into account the drawn system boundaries (district heating) or specifics of these heating systems (e.g. biomass heating systems). Since we used the price structure of retail consumers, some part of the upfront investments do account for variable energy costs. This is particularly evident for the tariff structure of district heating in Sweden and the Netherlands. Biomass technologies considered in this study use biomass as energy carrier compared to the other technologies, which means that all the necessary purification and other comparable processes, which have taken place outside the system boundaries chosen for the other technologies, have to be done within the chosen system boundaries.

3.4.4 Conclusions

The results of this analysis show that, even though the exergy content of energy carriers is reflected to some extent in the variable costs, this not necessarily has to be the case for the total heat generation costs. The reason is that additional capital expenses are required for making use of these low-exergy resources. Thus, capital costs level out the lower variable costs of low-exergy energy carriers.

This can also be formulated in terms of the possibility to substitute exergy with capital and hence reduce the consumption of high-exergy resources by additional capital input. This supports, for the cases studied here, the proposition that exergy and capital can substitute each other to some extent. As detailed in the literature review, exergy experts have been proposing metrics (e.g. exergoeconomic factor, exergetic cost factor) to define and quantify the relationship between monetary and exergetic costs (though in the literature this is mainly done for CHP and large scale industrial applications).

In our analysis, we bear in mind that using low exergy energy carriers usually requires the installation of more expensive equipment, which explains the higher capital cost but also entails more opportunities for technological improvement. Taking the case of Austria, if advances in technology would lead the capital cost to drop by 20 % for a low exergy heating alternative (e.g. heat pumps) this could potentially lead to a drop in total cost of about 20 €/MWh. For a high exergy heating alternative, e.g. direct electric heating in Austria, the share of capital cost is much smaller. Even if advances in technology did lower capital costs by 20%, that would only lead to a drop of about 5 €/MWh in total costs. Therefore the prospects of technological improvement appear in general more promising for low exergy alternatives when considering the sheer volume of physical capital alone.

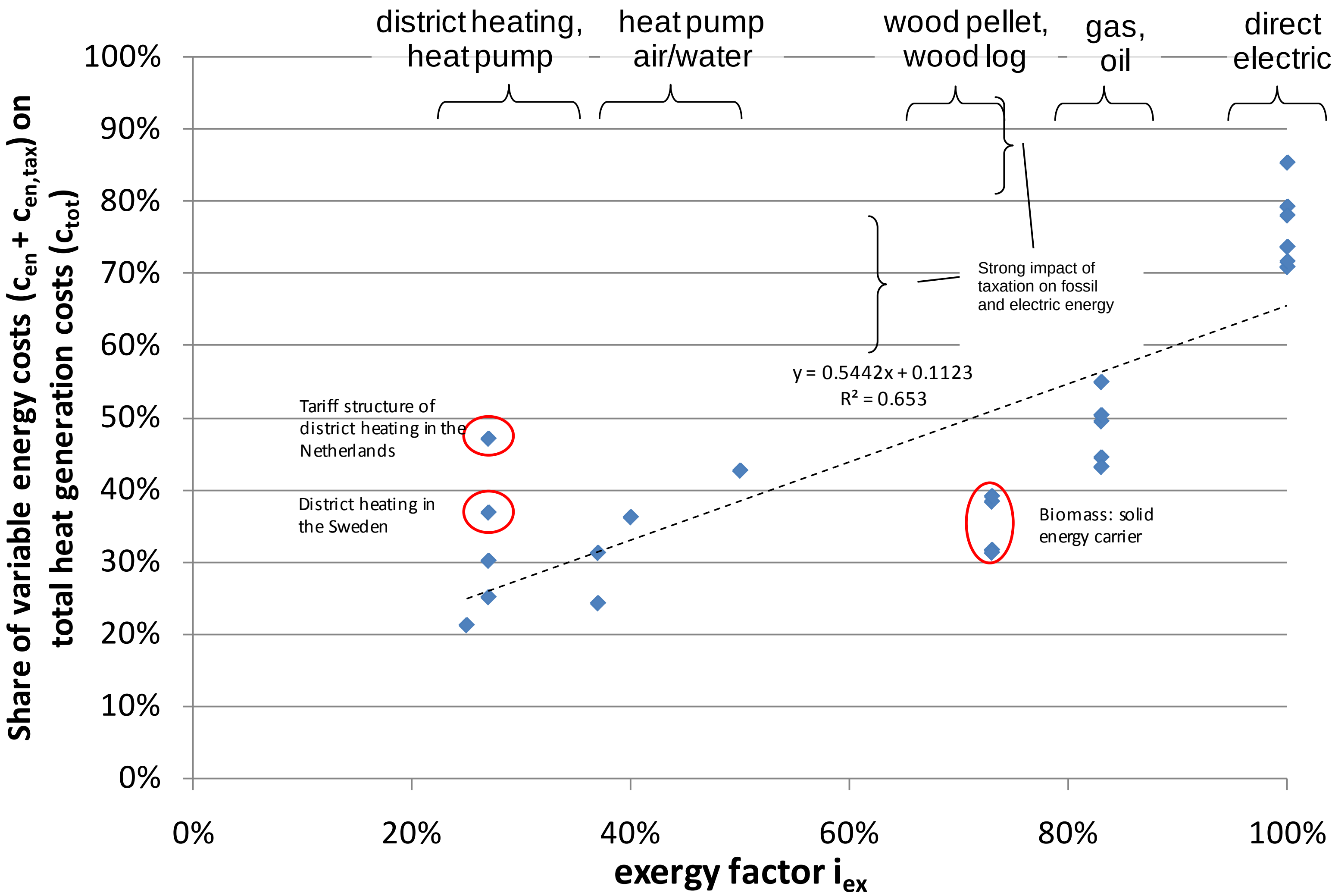

Figure 3. Share of variable energy costs on total heat generation costs for all technologies and case studies

Several questions are left for further research. In particular they refer to the following issues:

- extending the sources of energy carriers and systems (e.g. solar thermal systems),
- extend the system boundary (e.g. including the capital costs for gas or district heating grids),
- extending the exergy input with the exergy needs related to investments (e.g. boiler, district heating grid etc)

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Annex: Heating system cost data

		Wood log boiler	Wood pellets boiler	Gas boiler	Oil boiler	District heat (waste heat)	Heat pump air / water	Heat pump brine / water surface	Electrical convection type heater	Electrical night storage heater
Variable energy price	€/MWh	23	29	40	40	31	83	83	83	73
Energy taxes	€/MWh	0	0	5	11	0	17	17	17	17
Investment costs	€	10 728	13 645	10 915	10 298	11 085	11 417	16 417	2 565	3 794
Levelized investment costs	€/a	1 034	1 315	1 052	992	1 068	1 100	1 582	247	366
Operation and maintenance costs	€/a	297	352	202	270	443	233	194	21	30
Total fixed costs	€/MWh	67	83	66	63	98	70	93	17	24
Total heat generation costs with taxes	€/MWh	97	121	113	112	131	104	113	100	97
Total heat generation costs without energy taxes	€/MWh	97	121	120	125	131	110	118	117	114

Table 2: Energy costs, consumer prices and technology data for the heating systems considered in Austria

		Wood pellets boiler	Oil boiler	District Heat	Heat pump exhaust	Heat pump ground	Direct electric heating	Storing electric heating	
Variable energy price	€/MWh	34	33	31	53	53	53	48	(1)
Energy taxes	€/MWh	0	14	2	9	9	9	8	(T)
Investment costs	€	12 780	10 584	10 112	7 762	13 650	2 989	4 034	(2)
Levelized investment costs	€/a	1 231	1 020	974	748	1 315	288	389	(c)
Operation and maintenance costs	€/a	124	96	43	92	126	64	76	(1)
Total fixed costs	€/MWh	68	56	62	42	72	18	23	(c)
Total heat generation costs with taxes	€/MWh	110	96	95	69	92	71	72	(c)
Total heat generation costs without energy taxes	€/MWh	110	112	98	73	95	80	80	(c)

Table 3: Energy costs, consumer prices and technology data for the heating systems considered in Finland

		Natural gas	District Heating	Electric Heating
Variable energy price	€/MWh	38	50	125
Energy taxes	€/MWh	16	23	42
Investment costs	€	11 931	10 592	3 462
Levelized investment costs	€/a	1 149	1 020	334
Operation and maintenance costs	€/a	81	50	13
Total fixed costs	€/MWh	87	87	60
Total heat generation costs with taxes	€/MWh	134	140	184
Total heat generation costs without energy taxes	€/MWh	154	164	226

Table 4: Energy costs, consumer prices and technology data for the heating systems considered in the Netherlands

		Wood pellets boiler	Oil boiler	District Heat	Heat pump ground	Direct electric heating	Gas
Variable energy price	€/MWh	34	38	36	65	65	42
Energy taxes	€/MWh	0	32	0	24	24	21
Investment costs	€	12 396	10 672	19 810	15 844	8 517	10 241
Levelized investment costs	€/a	1 194	1 028	1 909	1 526	821	987
Operation and maintenance costs	€/a	323	215	120	161	0	215
Total fixed costs	€/MWh	65	53	83	72	35	51
Total heat generation costs without taxes	€/MWh	107	100	124	96	100	94
Total heat generation costs including energy taxes	€/MWh	107	139	124	105	124	115

Table 5: Energy costs, consumer prices and technology data for the heating systems considered in Sweden

CHAPTER 4

INNOVATIVE TECHNOLOGIES, CASE STUDIES

Introduction

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The previous chapters dealt with definitions, tools and sustainability (both environmental and financial) of exergy in the built environment. The present chapter presents four examples of LowEx approaches and tools applied to concrete cases of buildings and communities.

In the first section of this chapter, Molinari and Lazzarotto describe their simulations of a residential building in Sweden coupled to a ground source heat pump. They simulate interactions between soil, borehole, heat pump and building, taking account of the physical dimensions of boreholes and hence their effect on ground temperature in the course of heat removal during the winter season. They consider electricity and exergy flows associated to heat transfer, with and without mass transfer. In addition to using the well-established coefficient of performance (COP) figure of merit they propose a coefficient of exergy performance (COexP), which they define as a ratio of building exergy demand to exergy supplied to the heat-pump and fluid-pump. While the COP considers only electricity as an input, the COexP also takes into account thermal exergy provided by the ground to the heat pump evaporator, as well as the dynamic relationship between ground and environmental air temperatures.

In addition to quantitative results from simulations, the LowEx approach also lends itself to guiding the preliminary design and planning stage of building energy systems, as reported by Stefens and van der Kooi in the second section of this chapter. They apply exergy-based reasoning to the process of planning the energy systems of a sustainable campus in The Netherlands. The campus, Xperience Parkstad, groups four educational institutions from post primary to university, focusing on the sustainability of energy use in their real estate and in their educational programmes. To provide input for the energy system planning process, the authors organised a workshop in the present Open University campus, in the framework of the COSTeXergy action, whereby exergy experts joined staff and students of the educational institutions and other local actors. They applied exergy principles to answer a set of previously-formulated questions related to heating and cooling (integration with an existing mine water system of the Heerlen city) an electricity supply (biomass-fired power plant, possibly on a regional scale).

In the third section of this chapter, Wiercinski and Skotnicka-Siepsiak apply the Excel-based tool developed in IEA ECBCS Annexes 37 and 49 to steady state exergy calculations for heating systems. They perform quasi-steady analyses of seasonal thermal exergy supply and demand for a traditional and for a LowEx house in Poland. They consider the length of the heating season and the exergy losses through the heating system. For the cold climate in question, the error made by neglecting the humid air component of exergy is considered to be rather small.

In the fourth section of this chapter, Cesaratto, De Carli and Emmi apply exergy analysis to a case study of building renovation, from a building-services perspective. They examine and discuss the effect of intermittent and/or continuous heating system operation, considering the building envelope along with the efficiencies of emission, distribution/production and control of a traditional boiler, a modulating condensing boiler and a heat pump for different room set-point temperatures.

The four contributions collected for this chapter provide a relatively broad overview of how the low-ex approach can be applied to both dynamic and steady-state calculations, as well as to qualitative assessments of energy systems in the built environment. The final chapter of this book presents pioneering work by experts in the emerging field of exergy applied to human thermal comfort.

4.1 Dynamic exergy analysis of ground-coupled heat pumps for residential heating

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4.1.1 Introduction

In this section energy and exergy analysis is utilized to investigate the performance of a ground source heat pump system supplying low temperature heat to a floor heating system. Lohani (2010) and Lohani and Schmidt (2010) performed similar studies, considering the ground source to have a constant temperature. This simplification might give optimistic results, as indicated in table 3. The aim of this section is to illustrate how the exergy concept can be used to show where losses are incurred and to propose a useful indicator for the performance of the integrated system.

The ground is often seen as a stable heat source due to its rather constant yearly temperature a few meters below the surface. However, when heat is extracted or injected into the soil, the temperatures in the extraction and injection sites will change according to the design of the ground heat exchanger system - a pipe inserted in a borehole where a heat transfer fluid is circulated. The temperature difference between the heat transfer fluid and the surrounding soil entails a potential for heat transfer along the borehole. Therefore, for a given heat load, the longer the borehole, the lower the heat flux along the borehole and hence the lower the influence on the ground temperature. On the other hand, since investment costs increase with borehole length, the goal of the designer is also to optimize key economic parameters such as investment cost and payback time in the sizing process. The state-of-the-art procedure to design borehole heat exchangers consists of performing dynamic simulations of the borehole heat exchanger coupled with a building through a heat pump system; this allows the designer to evaluate the temperature variation of the ground source and therefore the heat pump performance during its life time for given design parameters.

4.1.2 Methodology

In the present work, a residential building using a ground source heat pump as a heating system is modelled as a case study. Figure 1 shows a sketch of the energy and calculation flows. The building heating demand is calculated using the IDA simulation environment (Equa) and provides input data for the MATLAB-based model of the heat pump and ground source heat exchanger.

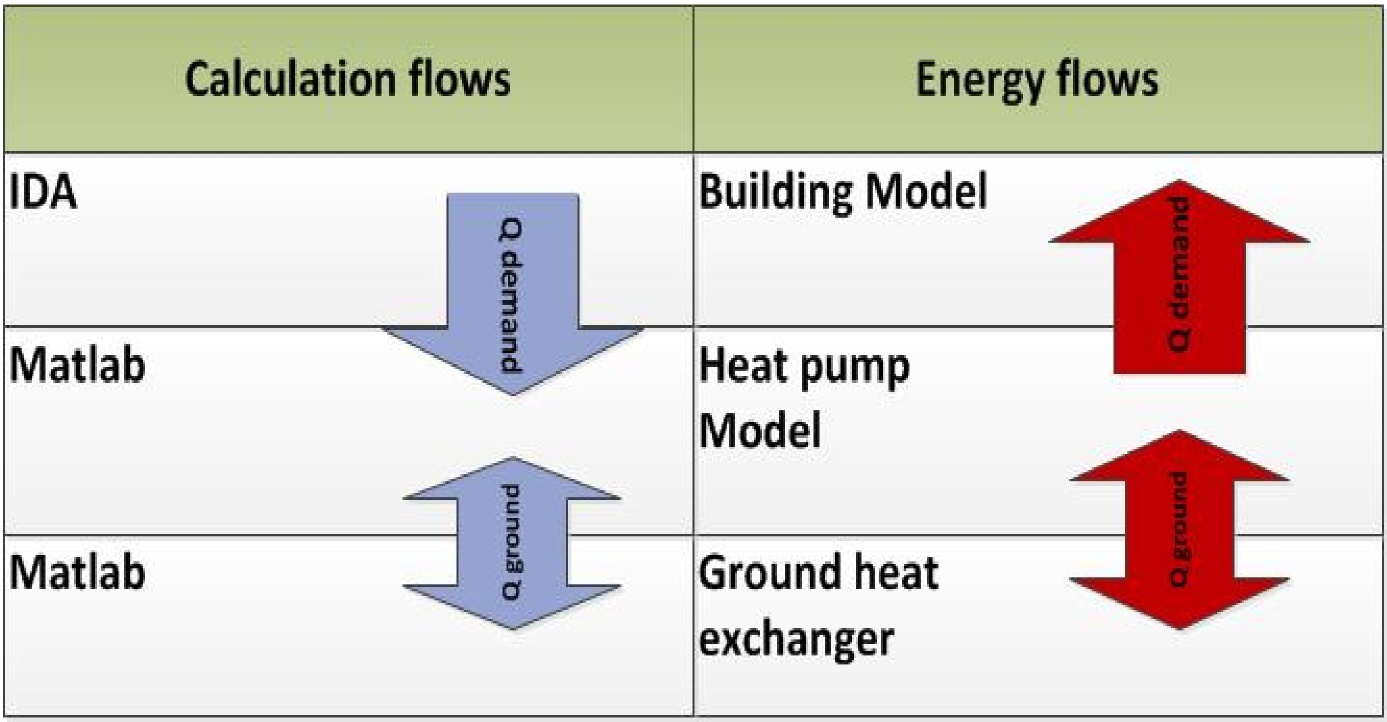

Figure 1: Scheme of the interaction between IDA and MATLAB. Q_{demand} is the heat demand in the building; Q_{ground} is the heat flow exchanged with the ground.

Building simulation

The semi-detached renovated house shown in figure 2 is assumed to be in a suburban area south of Stockholm.

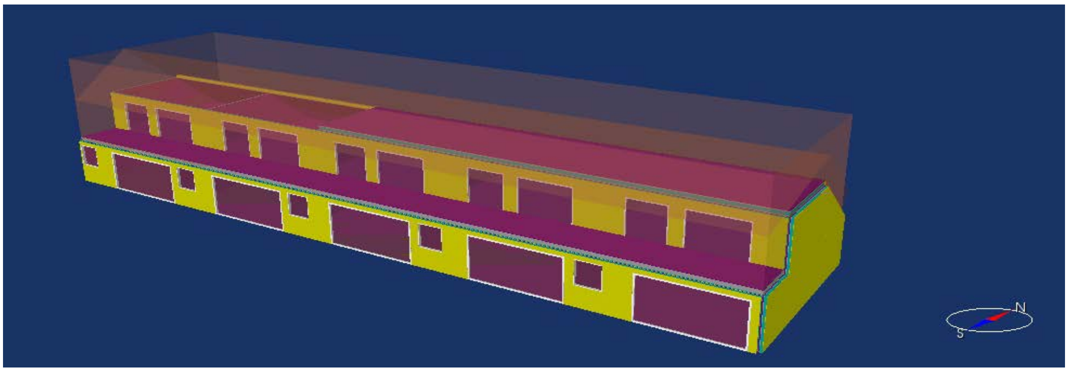

Figure 2: 3D view of the simulated building

Table 1 summarises the main descriptive parameters of the building. The building has 331 m^2 ground floor area and 941 m^2 envelope area respectively. The window/envelope ratio is about 12.4 %. The location chosen for the simulation is Stockholm (latitude 53.35 N, longitude 17.95 E) and the weather file used is SMHI-1977, Bromma airport. The building heat emission system is a floor heating system. Air is renovated by means of a balanced ventilation system at a rate of 0.35 $l/s \cdot m^2_{floor}$; a heat exchanger of 0.8 efficiency is used for heat recovery. Air tightness is 2 $l/s\ m^2_{floor}$ at 50 Pa and internal gains account for 3.18 W/m^2_{floor}.

Wall area [m²]	**Window area [m²]**		**Roof area [m²]**	**Ground floor area [m²]**	**Total heated area [m²]**
215	116		278	331	580
Wall U-value [W/m²K]	**Window U-value [W/m²K]**	**G-value [–]**	**Roof U-value [W/m²K]**	**Ground U-value [W/m²K]**	**Set-point temperature [°C]**
0.095	1.1	0.62	0.19	4.6	21

Table 1: Main parameters of the simulated building

Heat pump

The space heating demand of the building is met by a heat pump. The demand for domestic hot water is not considered in the calculations. The condenser of the heat pump is connected to the floor heating system and the evaporator to the ground heat exchanger.

The heat pump is modelled by approximating its actual coefficient of performance (COP) to the product of the ideal COP by an irreversibility factor η_{irr} which accounts for irreversibility at the compressor. In formulas:

$$COP_{act} = COP_{id} * \eta_{irr} = \frac{T_h}{T_h - T_c} * \eta_{irr} = \frac{\dot{Q}_{condenser}}{P} \qquad (1)$$

where T_h is the condensing temperature and T_c is the evaporation temperature of the refrigerant in the heat pump. $\dot{Q}_{condenser}$ is the heat/s supplied by the condenser to the floor heating system and P is the electric power supplied to the compressor. The temperature T_h is assumed to be 3 ºC higher than the inlet temperature of the floor heating; T_c is assumed to be 3 ºC lower than the inlet temperature of the ground heat exchanger. The irreversibility factor in the compressor, η_{irr}, is assumed to equal 0.5 (IEA Heat Pump Centre).

Ground heat exchanger

The ground heat exchanger model is implemented in the MATLAB environment. The procedure utilized is a standard method and consists of splitting the ground heat exchanger system in two zones, the borehole zone and the ground zone.

The borehole zone describes the thermal interaction between the heat transfer fluid and the soil at the borehole surface. A dynamic relationship between heat exchange and temperatures of the borehole and heat transfer fluid at a given time *t* is given by Hellström (1991), based on measurements:

$$T_b(t) - \overline{T}_f(t) = q'(t) R_b^*, \tag{2}$$

where $\overline{T}_f$ is the arithmetic mean temperature of the fluid between inlet and outlet of the ground heat exchanger, T_b is the borehole surface temperature, R_b^* is the so called effective borehole resistance, and *q'* is the heat per meter borehole extracted from the ground.

The ground zone describes the temperature variation at the borehole caused by heat injection and extraction into and from the ground. The ground is assumed to be a semi-infinite medium with initial temperature equal to the undisturbed ground temperature T_0, assumed to be 10 °C, due to the depth of the boreholes (120 m). Since heat transfer is assumed to take place only by conduction, it can be described by linear partial differential equations; superposition of effects in time and space can therefore be applied. As a consequence, the heat *q'(t)* can be decomposed into the sum of simpler step functions.

In literature, this method holds the name of *g-function method* (Claesson and Eskilson 1988). By using the following expression the temperature at the borehole can be calculated:

$$T_b(t_n, r) - T_0 = \sum_{n=1}^{n} \frac{q'(n) - q'(n-1)}{2\pi k_g} g\left(\frac{(t_n - t_{n-1})}{t_s}, \frac{r}{r_b} \right) \tag{3}$$

$T_b(t_n,r)-T_0$ is the temperature difference between the borehole field at an instant t_n and coordinate *r* and the undisturbed ground temperature T_0. This difference equals the sum over n time steps of the heat exchanged per meter $q'(n_i)$ at the time step *n* minus that at time step *n-1* multiplied by the *g-function* and divided by $2\pi k_g$; k_g is the thermal conductivity of the ground [W/(mK)]. The *g-function* represents the non-dimensional response function at the distance *r* from the source while heat is extracted from the ground. t_s is the steady state extraction time characteristic for the borehole and the operating procedure. In the present section, the *g-function* has been evaluated following the procedure suggested by Lamarche and Beauchamp (2007). Table 1 summarises the main borehole parameters.

Thermal conductivity ground [W/mK]	**Ground density [kg/m³]**	**Specific heat capacity ground [J/kgK]**	**Undisturbed ground temperature [°C]**	**Number of bore-holes N**	**Length of bore-holes L [m]**	**Distance between boreholes [m]**
1.8	775	2630	10	3	120	8

Table 2: Ground heat exchanger main parameters

The electric power for water circulation in the ground heat exchanger is calculated based on the friction factor, *f*, for a mass flow of 0.48 kg/s by assuming a pump efficiency of 0.7.

Exergy calculation

In this model three types of exergy flows are considered: electricity flows ($\dot{E}x_{el}$ Eq. 4), exergy flows associated with mass flows ($\dot{E}x_{mass}$ Eq 5) and exergy flows associated with heat flows ($\dot{E}x_{Q}$ Eq. 6). They are calculated as follows:

$$\dot{E}x_{el} = \dot{E}l \tag{4}$$

$$\dot{E}x_{mass} = \dot{m} * ex_{spec} = \dot{m}c_p\left(\left(T - T_{env}\right) - T_{env}\ln\left(\frac{T}{T_{env}}\right)\right) \tag{5}$$

$$\dot{E}x_{Q} = \dot{Q}\left|\frac{T - T_{env}}{T}\right| \tag{6}$$

In the above equations, *El* is electricity, $\dot{m}$ is mass flow rate and c_p is isobaric specific heat. The symbol *T* is used to designate absolute temperature, T_{env} being environmental air temperature (this section exceptionally uses T_o to designate soil temperature).

The instantaneous outdoor temperature is considered as the reference-restricted dead state for the exergy calculation.

The overall performance of the system is evaluated with two parameters: the actual COP (COP_{act}) and a coefficient of exergy performance (*COexP)* defined as follows based on work by Bilgen and Takahashi (2002):

$$COexP = \frac{\dot{E}x_{useful\_effect}}{\dot{E}x_{el}} = \frac{\dot{E}x_{demand\_building}}{\dot{E}x_{hp} + \dot{E}x_{pump}} = \frac{\dot{Q}_{supplied}\left|\frac{T - T_{env}}{T}\right|}{\dot{E}x_{hp} + \dot{E}x_{pump}} \tag{7}$$

Equation 7 equates the useful effect (Ex_{useful_effect}) to the thermal exergy demand of the building ($Ex_{demand\_building}$) that is equal to the exergy value of the heat supplied by the heat pump ($Q_{supplied}$), thereby neglecting thermal losses from distribution (e.g. due to imperfect piping insulation) and disregarding the efficiency of heat emission at room level. On the input side, Equation 7 considers the electricity supplied to the heat pump (Ex_{hp}) and to the heat transfer fluid circulation pump (Ex_{pump}).

Lohani (2010) uses exergy efficiency as a performance indicator, defined as the ratio between the output and input of exergy, where the input is the sum of the thermal exergy supplied to the evaporator and the electricity supplied to the compressor. This parameter decreases as the irreversibility in the system increases. However, it does not explicitly show how much of the exergy demand is met by electricity and how much exergy is related to heat input of the evaporator. The COexP is not insensitive to outdoor temperature since, when more thermal exergy can be supplied to the evaporator, less exergy has to be supplied as electricity to the compressor, for a given room temperature and a similar set of operating conditions. The COexP has the merit of considering the system within an environment at a given reference temperature. The COP, on the other hand, is a measure of energy (not exergy) performance. It is influenced by the temperature lift (since the required pressure lift for a given working fluid is related to the desired temperature lift between evaporator and condenser), the input of thermal energy into the evaporator is not explicitly taken into account. The COexP is considered to be a more holistic performance index from a resource-use viewpoint, because it also considers the exergy flows.

4.1.3 Results

The plot in figure 3 shows calculated temperatures for the ground-coupled heat pump at the condenser and evaporator, and the outdoor air temperature. The temperature of the secondary fluid at the evaporator side varies during the heating season, as does the environment air temperature. The plot shows that in the heating season the evaporator temperature is higher and fluctuates less than the environment air temperature. Exergy flows in the system are derived from the temperature variation of the heat carriers at the evaporator and condenser side, and the instantaneous outdoor air temperature.

Figure 4 shows the heat demand of the building, the instantaneous COP and the COexP. The heat load is maximum and roughly stable in the first and last two months of the year. The COP increases in the warmest months of the heating season (months 2-4 and 8-10). This trend differs from the COexP, which is highest in the coldest months of the heating season. This is due to the fact that the thermal exergy contribution of the ground is evaluated according to the environmental conditions. In the coldest months the ground is at a higher temperature than the environment, thus delivering warm exergy to the evaporator, whereas in the warmest months the ground is at lower temperature than the temperature of the environment.

The COexP values have a lower magnitude than the corresponding COP values because of two reasons. On the one hand because the heat pump operates very near to environmental temperature (which entails heat flows of rather low exergy) and on the other hand because the COexP takes into account the ambient heat that is supplied to the evaporator. Alternatively, the COP overlooks interaction with the surrounding environment, as it excludes from the energy balance the ground heat supplied to the evaporator, and also disregards how the outside air temperature influences the value (i.e. the thermal exergy) of the heat delivered by the condenser.

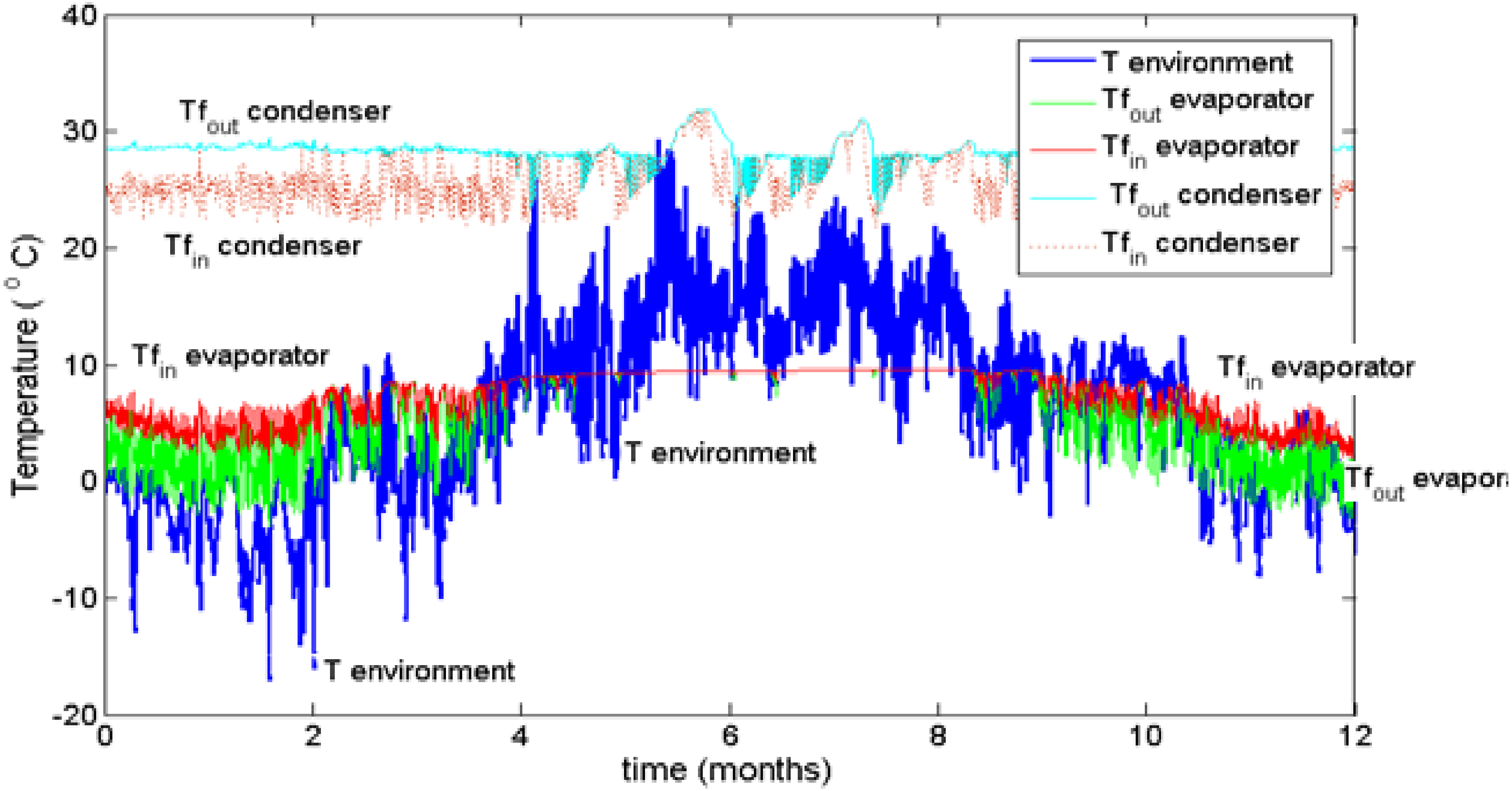

Figure 3: Main temperatures in the system for 1-year simulation time

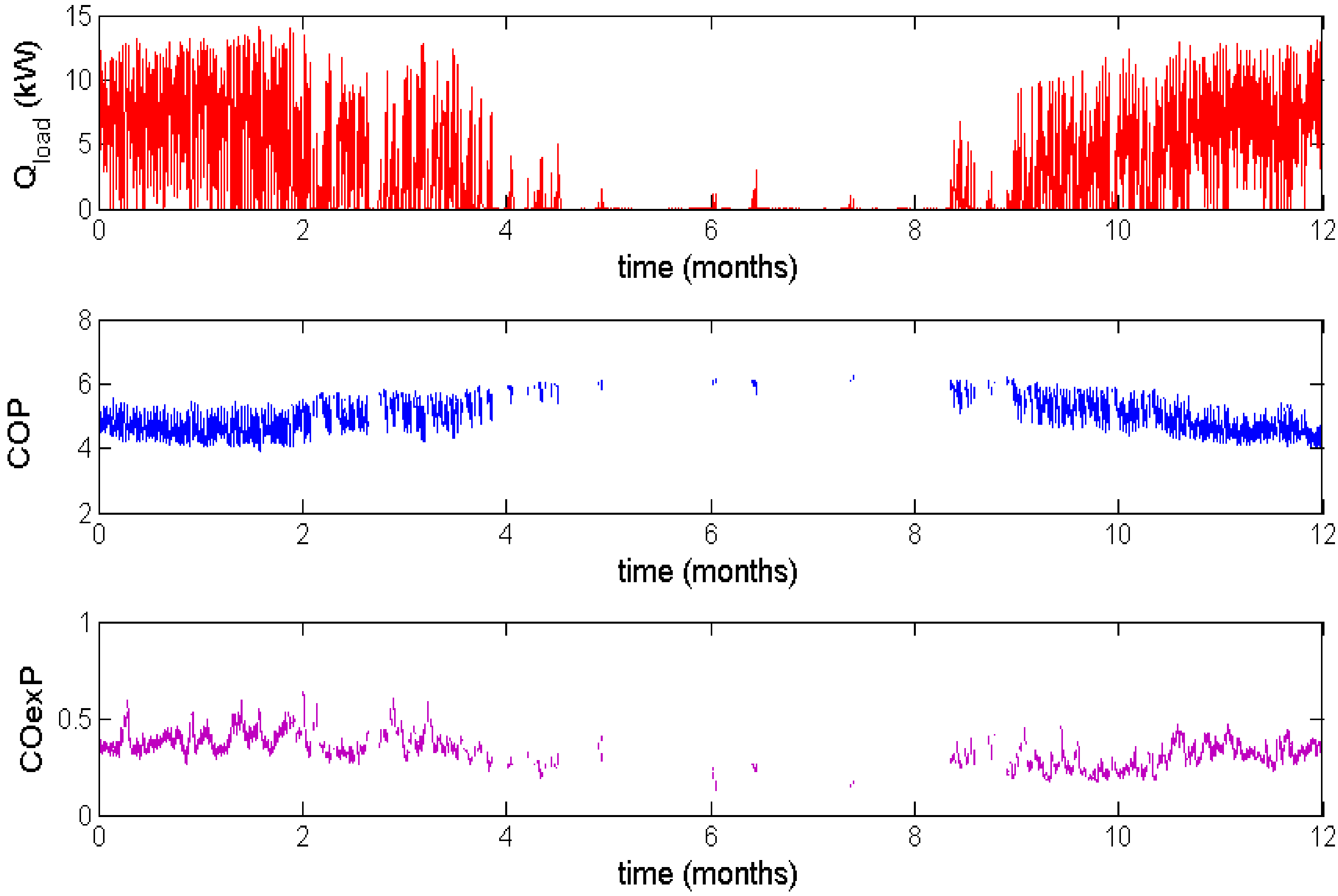

Figure 4: Heating demand, COP and COexP of the heat pump for 1-year simulation.

A better insight into the interaction between heat pump and ground source is given in figure 5. The figure shows the exergy provided by the ground to the evaporator divided by the power provided to the compressor. A positive value indicates that the evaporator (which receives heat from the ground) provides warm exergy to the heat pump when the ground is at a higher temperature than the outdoor environment. On the contrary, a negative value of the ratio indicates that the ground temperature is below the air temperature. In the coldest months of the year the energy demand for heating the building increases and so does the heat transfer from the ground heat exchanger to the evaporator. As a consequence, the temperature in the ground falls below the environmental air temperature. The power required by the compressor is then higher than it would be if the ground were a perfect sink at the same temperature as that of the environment.

This can be further highlighted by the following Grassmann diagrams. Figure 6 shows the overall exergy flows of the heat pump working under two different conditions during the year. On the left, exergy flows from the ground to the evaporator. The ground is at a higher temperature than the outdoor environment and it transfers both energy and exergy to the heat pump system. On the right, thermal energy still flows from the ground to the evaporator, but exergy flows in the opposite direction because the ground temperature has become lower than the environmental air temperature. The COexP is respectively 0.57 and 0.19 in the first and second case while the exergy efficiency is respectively 0.46 and 0.21.

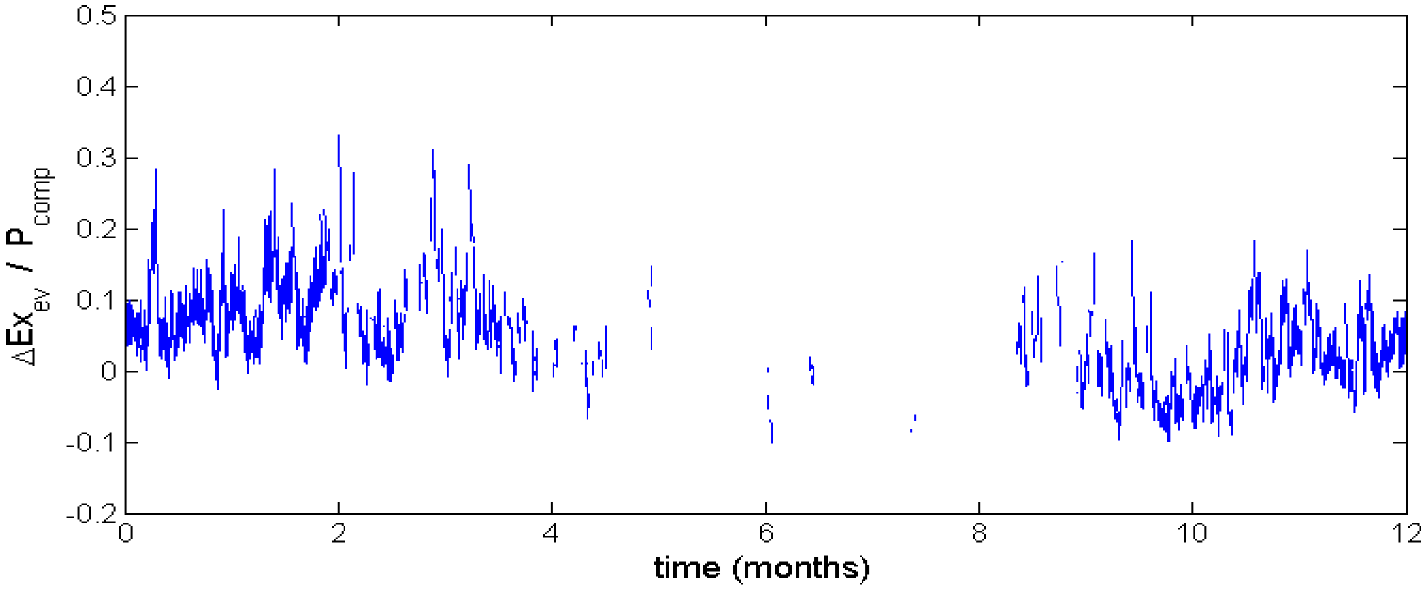

Figure 5: Ratio of thermal exergy input from the ground to electric exergy input to the compressor.

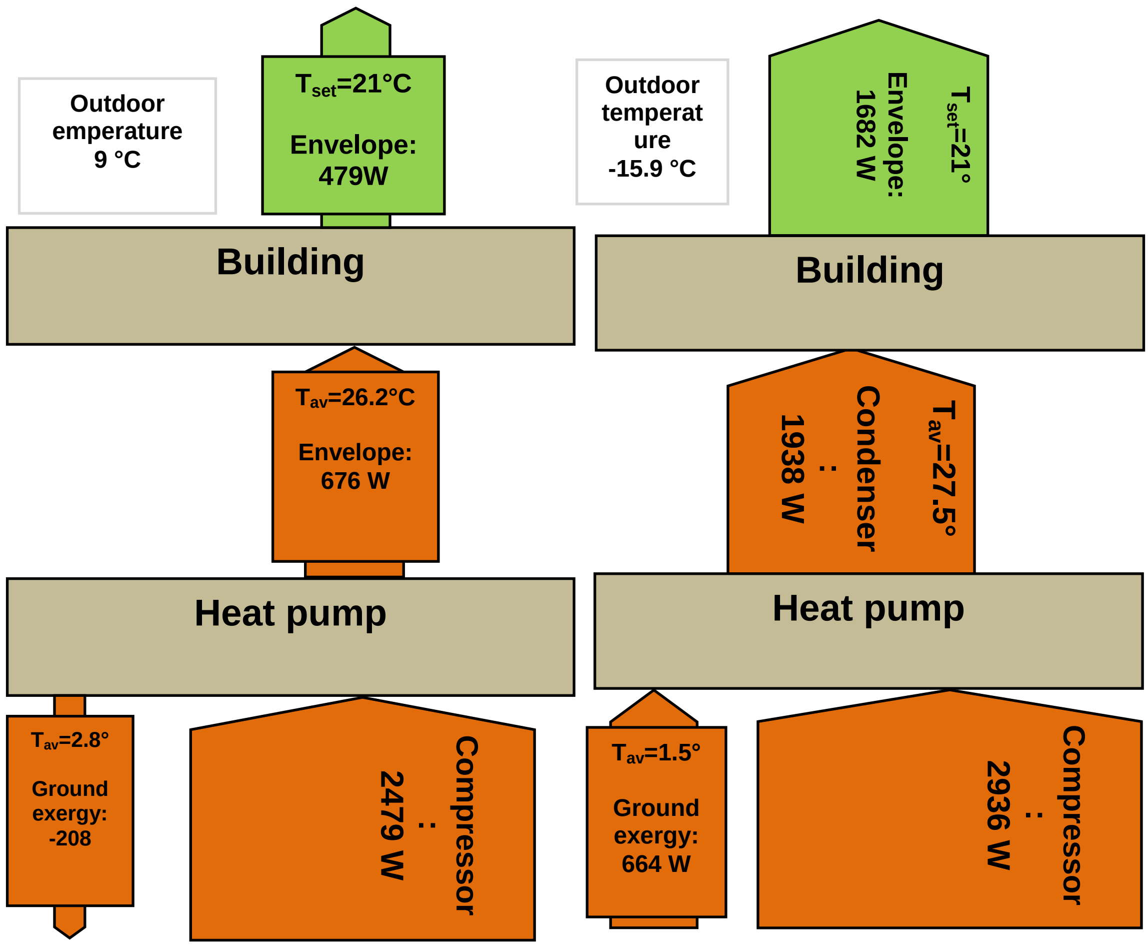

Figure 6: Grassmann diagrams of the exergy flows in the system in two different conditions.

The overall performance of the system is evaluated based on seasonal values of COexP and exergy efficiency. These figures are obtained from the instantaneous values using the exergy demand as a weighting function. Table 3 compares seasonal exergy efficiency and seasonal COexP for the case studied and for a ground source with constant temperature. The seasonal COexP yields higher values compared to exergy efficiency (η_{ex}) for all the investigated cases. When the ground source contributes very small amounts of thermal exergy, both performance indexes yield similar results. When the exergy that can be extracted from the ground is more relevant, the difference increases.

Another aspect highlighted by table 3 is the importance of considering real ground heat exchanger configurations. Neglecting the physical dimensions of boreholes, and hence their effect on ground temperature, would lead to the assumption of constant ground source temperature, which would lead to an overestimation of the system exergy performance.

	η_{irr} = 0.5			η_{irr} = 0.4		
	η_{ex}	COexP	COexPpump	η_{ex}	COexP	COexP pump
Boreholes = 3 × 120 m	33.84 %	36.05 %	35.2 %	27.7 %	29.29 %	28.72 %
Boreholes → infinite	37.47 %	44.6 %	-	31.22 %	35.79 %	-

Table 3: Comparison of seasonal exergy efficiency and seasonal COexP for different study cases. The spacing between the boreholes is 8 m in both cases. The COexP pump also takes into account the circulation pump work.

4.1.4 Conclusions

Energy and exergy flows are modelled for a residential building coupled to a ground source heat pump (GSHP) and considering ground temperature variations due to thermal interaction with the GSHP. The overall performance of the GSHP system is evaluated in terms of COP (derived from the ideal COP for simplicity) and of COexP, which is a coefficient of exergy performance.

While the COP considers only electricity as an input, the COexP also takes into account thermal exergy provided by the ground to the heat pump evaporator.

In the coldest periods, the ground temperature is higher than the environmental air temperature, and hence the ground behaves as a supplier of warm exergy to the heat pump system. Since the ground heat exchangers and the surrounding soil are not infinitely large, continued operation of the GSHP in cold weather conditions may eventually result in lowered ground temperatures around the borehole heat exchangers. Towards the end of the winter, ground temperatures may thus be lower than environmental air temperature. This entails a bigger temperature lift, and hence a lower COP, for the GSHP than for a comparable air-source heat pump. Assuming the ground source temperature to be constant could thus lead to overestimating the performance of the system after continued operation under cold-weather conditions, depending on borehole heat exchanger configuration relative to building heating demands.

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4.2 Xperience Parkstad: Campus and Energy Supply System

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4.2.1 Introduction

This section presents information about cooperation between four different educational institutions, from post primary education to university, focusing on the sustainability of energy use in their real estate and in their educational programmes, with the aim of realizing one sustainable campus.

This cooperation has been formalized in a new institution named Xperience Parkstad. This section discusses issues relevant for the development of this green campus, and presents information related to the realization of a sustainable energy supply system aimed at reducing fossil fuel related CO_2 emissions, eventually to zero. This information also provides essential elements that can be considered a suitable base case and benchmark for international cooperation aimed at developing more sustainable campuses in general. From this perspective, a proposal on “Sustainable Education, Institutions, and their campuses, a first step towards sustainable societies” for a new COST Action was submitted to the COST office.

During the Heerlen meeting of Work Package 2 (WP2) of the COSTeXergy Action, suggestions for improvements of the Campus energy supply system were generated. These are described in item 4.2.3.

Item 4.2.1 outlines the context of Xperience Parkstad, and item 4.2.2 presents information about the campus site, the buildings, and the actual energy use, along with the foreseen improvements in buildings and energy supply system. Item 4.2.3 focuses on the questions discussed during the Heerlen meeting of WP2, together with additional information about the old coal mine and the mine water system. Item 4.2.4 presents answers to these questions obtained in the meeting, and item 4.2.5 the conclusions.

History

The Open University in The Netherlands started an investigation in 2005 to explore the possibility of using water from an old coal mine in Heerlen to heat and cool (part of) its buildings.

The first part concerned the investigation of the feasibility of drilling a hole to the gallery system of the old mine from their own building site. The second part concerned the necessary adaptations to the architecture and technical installations of the existing estate.

The result of the first part of this investigation was negative because, the galleries did not extend below the building site. Due to technical and legal complications when using directional drilling this case was not considered further. However, the option to make a connection to the extended mine water grid, and to use this water for heating and cooling purposes, was investigated. The municipality of Heerlen wants to invest in extending the mine water infrastructure to make the system more accessible. The second part of the investigation has been completed (Tongeren et al., 2007).

The necessary measures have been drawn up in an inventory of the existing building stock from the nineteen hundred eighties, to the buildings suitable for the use of a low exergy infrastructure. From an economic point of view this is only possible when substantially subsidized.

Cooperation

The wish to reduce the amount of energy necessary and to make use of more sustainable energy sources led to the installation of a taskforce: “Greening the Campus”. This taskforce developed a programme to implement technical measures and to raise staff and student awareness of the interactions with our environment. Cultural change and involvement is an important goal. For students this can be realized via their courses and through experience e.g. in self-owned small businesses. Furthermore, staff is invited to come up with ideas, lectures are organized, relevant information and articles appear regularly on the intranet and in personnel newsletters.

The three educational institutions (the Open University (OU), University College Zuyd (UCZ), and the Sintermeerten High School (SHS)) are located close to one another. Some time ago they decided to cooperate on education, with an important focus on sustainability issues, in order to better help students to build on their strengths and prepare them for their professional careers. This cooperation includes their real estate and the realization of one campus site. Recently the Arcus College (AC) joined in this cooperation, and in the near future they will realize new buildings on the campus site. This provides the possibility of integrating education from high school to university, including schooling for practical professions. It is now possible to extend “Greening the Campus” to formulate a common energy vision for the four institutions. This energy vision now includes pursuing the development of a CO_2-neutral campus (Stefens, 2009). The students and the institutions will be maximally engaged in its realization by means of research projects and by working in small business units. The cooperation is now formalized in Xperience Parkstad.

As indicated before, the overall transition of the existing real estate to low exergy buildings is (too) expensive. Therefore, the possibility to make use of green energy, such as PV, biomass, and wind, was investigated. After this analysis it became clear that the most realistic option was to build a biomass derived/based power plant, combined and integrated with the mine water system and an increased use of PV in the course of time.

A biomass based power plant was investigated in more detail in a case study supported by the Dutch ministry of economic affairs via the national organization Agentschap NL (Stefens, 2009).The ambition was to realize a CO_2 neutral campus by locally producing 80% of the necessary electricity and all heating and cooling. Because of the different types of buildings on the campus, a cascaded heating system and a connection to the mine water system would be necessary.

Gradually, it became clear that the integration of the energy supply system of the campus and the mine water system provided advantages for all parties and offered an even wider perspective: the realization of a sustainable regional energy supply system making use of sustainable energy carriers. This possibility was further discussed during a work-conference in November 2009. During this conference the municipality of Heerlen and Xperience Parkstad signed a declaration of intent to investigate the possibilities of integrating both systems.

Ambition

The “Leitmotiv” for the development of Xperience Parkstad’s new campus is sustainability, which is understood to imply both education and the physical layout of the campus. Students will be involved in and confronted with related sustainability problems. Hereby cultural change and involvement form important goals.

Xperience Parkstad has far-reaching energy and climate related ambitions. The construction,, maintenance, renovation and exploitation of buildings and infrastructure of the campus will be realized as much as possible in accordance with the Cradle-to-Cradle principle, so as to realize a transition to a sustainable campus. The short term goal is a CO_2 emission reduction of at least 50% compared to 1995. This reduction will be realized by the implementation of solutions in accordance with the so-called principle of “Trias Energetica” and by the use of sustainable energy sources. The longer-term goal of Xperience Parkstad is a reduction of the fossil fuel related CO_2 emission of 80% in 2025. The use of a sustainable collective energy supply system, an optimal energy infrastructure and building related measures can make this possible. Low exergy resources from the direct environment will be used as much as possible.

Last but not least, the challenge for Xperience Parkstad is to integrate students from four different educational cultures in an inspiring, lively, safe, and sustainable campus. This entails offering more personal and integrated education programs, according to students’ talents; making use of learning by doing (contact with companies); facilitating transition from one institute to another; and integrating sustainability in educational programmes.

The campus case

During a WP2 meeting in Heerlen in April 2009 three previously-formulated questions related to the energy supply system of the campus were answered by COSTeXergy participants, as presented in this paper. These questions concerned the possibilities of integration with the mine water system of the Heerlen city, the preferable type of biomass to be used as feed for a power plant, and its efficiency with regard to the possible construction of a regional biomass-fired power plant.

4.2.2 The campus

Figure 1 gives an overview of the campus site. The road that divides the campus in two parts is the Valkenburgerweg, which in the future must be integrated in the campus area as much as possible. The other, curved road, leads to the inner city of Heerlen, the railway station and important motor roads. In future these two roads have to be redesigned. The campus as a whole has to be redesigned as a coherent site in the near future, and several ideas are already being developed.

Figure 1: An overview of the campus site of Xperience Parkstad.

The buildings

Overview of the existing situation as of writing:

The Arcus College (AC) is not yet present on the campus.

The Open University (OU) has a gross floor area of 20,385 m^2, with buildings from 1984 up to 2002, traditional high temperature heating system (natural gas), limited possibility for balanced ventilation, cooling only of the main-frame computer space and the highest located offices.

The Sintermeerten High School (SHS) has a gross floor area of 10,350 m^2, building completed in 1993, high temperature heating system, mechanical ventilation and limited local cooling system.

The University College Zuyd (UCZ) has a gross floor area of 38,041 m^2, building activities completed in 1999, ventilation: 40% natural and 60% balanced, traditional high temperature heating system, low temperature cooling by using air handling and fan-coil heat exchanger units.

The buildings of the OU are located in the South East area of the campus and those of SHS in the South West area, next to the OU. The AC-Valkenburgerweg, under construction as of writing, is located just North of these Institutes. UCZ is located next to AC-Valkenburgerweg in the North East.

The other buildings located at the campus area are those of AC-Coriopolis, indicated in black, which are not yet under construction.

New buildings for the technical education programs of AC-Valkenburgerweg (gross floor area of 25,000 m^2) and AC-Coriopolis (gross floor area of 8,760 m^2), next to UCZ, were finished in 2012. Also for the OU new buildings are planned with a gross floor area of 10,000 m^2. These buildings, likely ready in 2016, will have limited heat transfer through the building envelopes, so that low temperature heating and high temperature cooling can be applied.

In the period from 2010 – 2025 the existing building stock will be improved substantially, at “natural” renovation moments of buildings and building services, in the most sustainable way and within financial constraints. The main goals of the planned maintenance, renovation/rehabilitation and construction of new buildings are reduction of energy use and improvement of air quality in the buildings, in the most sustainable way. After completion, only low temperature heating and high temperature cooling will be necessary throughout the year.

In the period after 2025 many of the buildings will have been renovated/rehabilitated, resulting in a substantial reduction in energy demand for heating and electricity. This also entails consequences for the building envelopes. Consequently, the energy will come from sustainable sources: direct use (PV, solar boilers etc.), and indirect use (biomass, wind etc.) of solar radiation, and from the (extended) mine water system.

Actual energy use

Table 1 gives an overview of the use of electricity and natural gas, and of the related CO_2 emissions for the four institutions, mainly based on data from 2006 and 2007 and without rounding up the resulting figures.

Institution	Electricity [MWh/yr]	Natural gas [m^3/yr]	CO_2 – electr. [kg/yr]	CO_2 – gas [kg/yr]	CO_2 – total [ton/yr]
AC	2,013	578,619	1,314,489	1,027,049	2,342
OU	1,600	210,000	1,044,800	372,750	1,418
UCZ	2,965	363,952	1,936,145	646,015	2,582
SHS	310	66,000	202,430	117,150	320
Total	6,888	1,218,571	4,497,864	2,162,964	6,662

Table 1: Overview of the total amount of electricity and natural gas used by the four institutions during a year, and of the related CO_2 emissions.

Building related improvements

From a cost-efficiency point of view an overall heat transfer coefficient U = 0.25 W/m^{2}K was chosen for the building envelope, the roof and the ground level floor of the improved buildings. For glazing it was chosen for HR++ glass with U = 1.1 W/m^{2}K. The air permeability of the building envelope is $q_{v,10} \leq 0.4$ dm^3/s per m^2. Heating and cooling systems to be applied are: floor and wall and when possible thermally activated concrete. Because sound-absorbing ceilings will be used, it will not be possible to use the ceilings for heat transfer to or from the rooms. Natural ventilation will be replaced by balanced ventilation. The hot water used for SHS's showers in their sports facilities will be produced in a solar boiler system.

The electricity demand will be reduced as much as possible e.g. by more efficient lighting systems, day lighting systems and presence detection. The new ICT equipment must be efficient and the cooling demand must be minimized.

After the building related improvements, the use of electricity and natural gas, and the related CO_2 emissions, are foreseen to be as shown in Table 2 (without rounding calculation results).

The building-related improvements should lead to reductions in electricity use of 1,700 MWh/yr and in natural gas use of 470,000 m^3/yr. This corresponds to reductions of 25% in electricity and 40% in natural gas use.

Institution	Electricity / [MWh / yr]	Natural gas / [m^3 / yr]	CO_2 –electr. / [kg / yr]	CO_2 – gas / [kg / yr]	CO_2 – total / [ton / yr]
AC	1,720	287,000	1,123,160	509,425	1,633
OU	1,000	143,000	653,000	253,825	907
UCZ	2,131	239,000	1,391,543	424,225	1,816
SHS	250	45,000	149,537	71,000	320
Total	5,101	714,000	3,317,240	1,268,475	4,576

Table 2: Overview of the yearly electricity and natural gas use and of the related CO_2 emissions, after building related improvements.

4.2.3 Questions and information for the Heerlen workshop (Work Package 2 of the COSTeXergy Action)

In order to realize a sustainable campus energy supply system, in a reasonably short time and within given financial constraints, input from the COSTeXergy Action was sought by organizing a Work-Package 2 meeting in Heerlen-NL in April 2009, where three previously formulated questions had to be answered:

- what will be the most optimal integration of the energy system of the campus and the Mine Water System (MWS)?
- what is the preferred kind of bio fuel for the power plant, possibly on the campus site?
- what is the optimal maximum power output of this power plant? Is it possible to consider not only the campus of Xperience Parkstad, but also a larger area around this campus?

Information about the mine water system (MWS)

Figure 2 gives an idea of the coalmine still in operation. The installations on ground level are indicated as well as the galley system under ground. The old maps of the galleys still exist and these are now accurately connected with the positions on ground level. This makes it possible to drill accurately to well chosen positions underground.

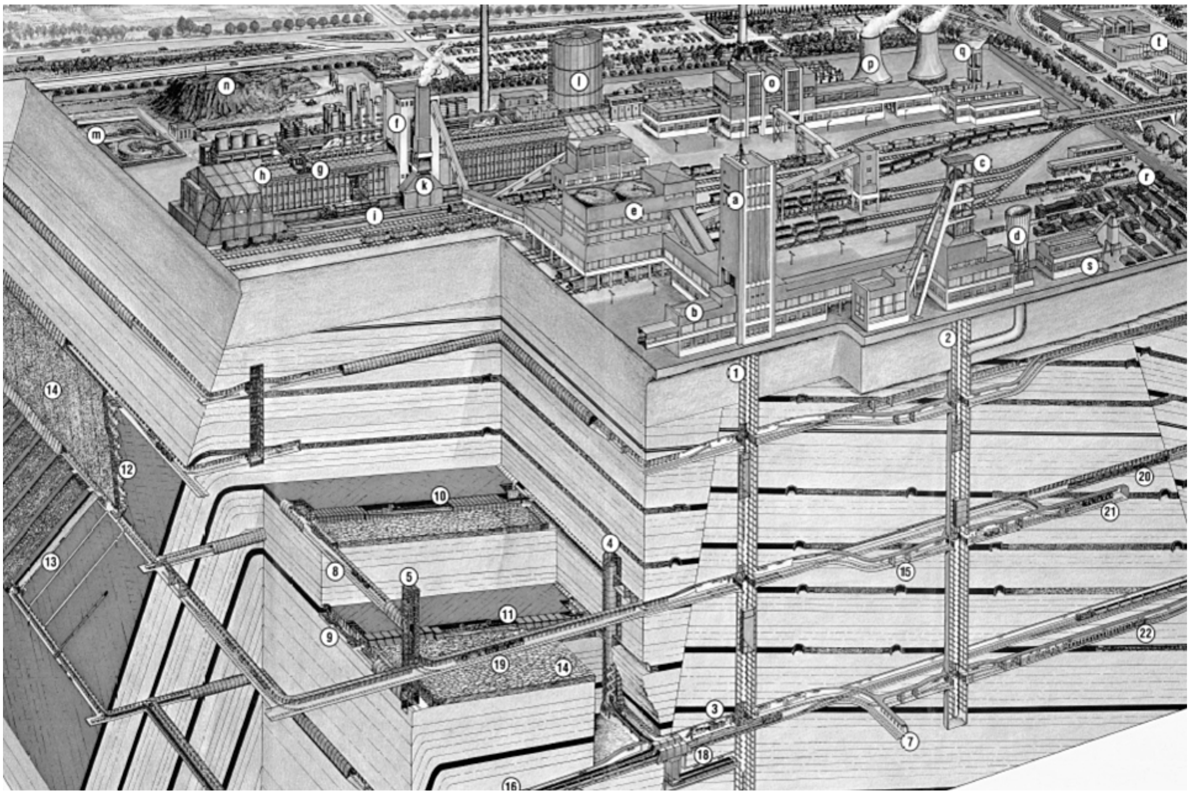

Figure 2: The coalmine still in the production phase

The former coal mine is not in operation anymore and the old galleys are now filled with water/broken stone. Measurements indicate that 70% of the galleys are still open and connected. The mine is located in the municipality of Heerlen and the possibilities to use this mine water for heating and cooling have been investigated. A grid of three different pipelines is available, but not yet extended to the campus of Xperience Parkstad. One of the pipes is used for hot water, one for cold water, and the last one for the return water. At this moment the mine water plant is in operation but not yet at its maximum capacity. There is opportunity for connection of the campus to the MWS.

Relevant data for the MWS

Capacity of the reservoir: $0.9*10^6 m^3$ hot water and $3*10^6 m^3$ cold water.

Temperatures: hot about 303K and cold about 289K.

Maximum capacity of each well: about 150 m^3/h.

Pipes of the transportation system: maximum allowable temperature 328K.

A schematic impression of the MWS is shown in Figure 3, where the total depth indicated is 800 m. The white construction on ground level is the mine water plant. The black vertical pipes indicate (the boreholes and) the piping needed for the underground withdrawal of warm water. Return water flows back to the underground via the white pipe, extending to intermediate depth. The shortest pipes, on the right, are used for withdrawal of cold water from the MWS.

4.2.4 Answers to the questions

This item presents the answers formulated during the Heerlen WP2.

First question – Mine Water System

In the long term all buildings can be heated and cooled by low temperature heating and high temperature cooling. The question is then: is it possible to cope with the maximum heating demand? When this is not the case heat pumps can be used to heat return water from the heating system to the appropriate temperature, using cooling water from the MWS. The cooling water of the MWS is then cooled and can be transported back to an appropriate well, so as to be used in summer for cooling.

From the available data, it can be expected that the cooling capacity of the MWS is enough for the maximum cooling load of the campus. The heated water can be returned to the appropriate well and level.

It would be more reasonable to produce electricity at or near the campus site, as in most cases the production of electricity also leads to a thermal energy stream as a by-product. When such a power plant would be designed for the maximum electric power needed on campus, the heating potential of the surplus thermal energy stream would likely exceed the campus heating needs. It must be investigated if further heating of the hot mine water would be a reasonable option.

Two important questions must be answered:

- what are the contributions to heat transfer through the walls of the galley system?
- what is the flow of water as enhanced by pumping water from and to this system?

The appropriate points from where water is pumped from and to the galley system must be determined in more detail, as well as the stability of the temperature gradient from the lowest level up to ground level, in view of this water circulation. The main problem to be solved is the determination of the capacities to store hotter water, intermediate temperature water, and colder water in a “stable” way in the galley system. From this it may be clear that the whole energy system of the buildings connected to the MWS has to be optimized in view of underground hydrothermal conditions.

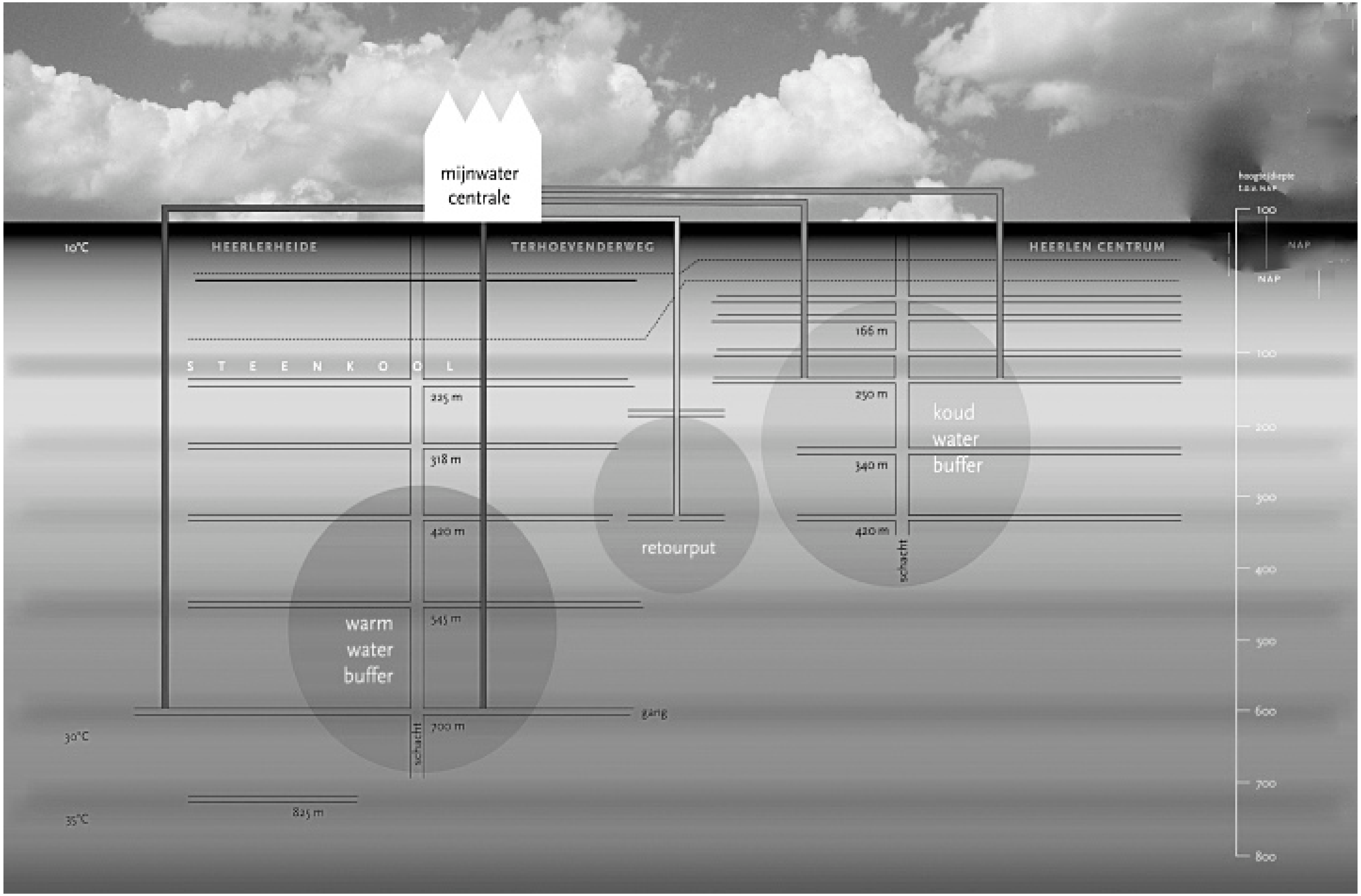

Figure 3: Schematic representation of the Mine Water System (MWS) in Heerlen

Due to the presence of cool water in the MWS, the cooling demand of the campus must preferably be met by drawing on cooling capacity from the MWS, when economically feasible. Most other means of cooling need extra provisions and would require energy, on the campus site or at the place where the cooling water comes from, and lead to a less sustainable solution. For example, it is well known that sorption cooling needs thermal energy at a sufficiently high temperature level to thermally drive a cooling cycle. The temperature needed to sustain endothermic desorption is higher than the temperature whereby thermal energy has to be removed in order to sustain exothermal absorption or adsorption. Furthermore, like in compression-driven cooling, heat has to be removed from the condenser. The amount of energy involved thus corresponds to the sum of the thermal energy supplied at the highest temperature level, plus the thermal energy removed at intermediate temperatures, plus any electricity used for pumps, valves and controls.

On the other hand, when thermal energy is stored underground electric energy is needed to extract and re-inject heat transfer fluid. At locations where underground temperature is strongly influenced by depth, exergy analysis can help develop new insight into optimal heat storage depths, considering the trade-off between the low-grade heat and high-exergy electricity involved (Asada and Boelman, 2004).

Second question – sustainable biomass production and use

When using biomass as a feedstock for a power plant one must realize that biomass must be used in such a way that biodiversity is maintained at the actual level, and preferably increased. Furthermore, biomass supplies us with food and fodder, is used for products such as the construction of (part) of our houses, and is also an energy carrier. This means that attention must be given to find the best option to make use of biomass to produce thermal energy and electricity. First it will be necessary to say something about the composition of biomass.

Biomass contains in general: water, sugars, most often combined in larger molecules e.g. cellulose (a polymer of glucose), lignin, proteins, oils, fats, minerals and special substances e.g. fragrances, insecticides, and antiseptics.

Biomass must preferably be used in such a way that the quality of the soil on which the biomass grew is maintained as much as possible. This means that the minerals must be returned to the soil before new biomass is grown on that soil. This can implicate that the biomass must be treated in such a way that a water-rich minerals stream is separated from the biomass. An important point to note further is that an appropriate amount of organic material must be available for all life forms present in the soil to feed upon to maintain/enhance this quality aspect of the soil.

Burning of biomass, e.g. to produce electricity, leads to the formation of volatile mineral components and to (solid) ash formation. The presence of these volatile mineral components implies that the hot combustion gases must be cooled down to a temperature where liquids are no longer present, and where only gas and solids remain. Then the combustion gases can be cooled further in heat exchangers to produce steam and generate electricity by making use of a turbine/generator system. The ash and the solids from the combustion gases cannot be returned directly to the soil because of the possible negative effects and the completely different solubilisation characteristics of most of these solids. This is the reason why these solids go to landfills, and are used in road construction and cement production. Due to the necessity of cooling the combustion gas, the energy efficiency of electricity production is in the order of 30%.

The option that complies most with the sustainability ideas presented above is anaerobic fermentation of biomass, to produce a gas mainly containing methane and carbon dioxide, in addition to organic material still containing the minerals. These so called leftovers of the digester can in principle be returned to the soil to restore the soil quality and to improve that quality by the organic substances present in the leftovers of the digester. In this way, also human excrement and organic material from kitchens can be used as feedstock in this process. In these cases, substances that cannot be digested and substances causing harm in the environment must not be present in the human excrement or in the organic material from the kitchen(s).

In the near future, the best option is to separate the biomass into its main components (in a so called bio-refinery) and to make use of these components in the best and most sustainable way. For example, it is possible to produce different qualities of wood mainly from differing amounts of cellulose (hemi-cellulose etc.) and lignin, and also depending on the quality of the cellulose fibres. The large molecular substances, such as cellulose, can be hydrolyzed to produce the sugar monomers. From these monomers, ethanol can be produced by fermentation. Ethanol can replace gasoline in combustion engines to drive cars. Ethanol mixed with water can be used as fuel in power stations to first produce electricity in a gas turbine/generator combination and then in a steam turbine/generator combination to produce electricity with an efficiency of about 55%. The liquid ethanol fuel for cars and the electricity produced from ethanol-water mixtures can be sustainable to a large extent.

The proteins are very valuable as essential components of food and fodder, and can reduce the necessity of the cultivation of some crops. In addition, pharmaceutical products can be derived from proteins. Oils and fats are energy-carriers in food and fodder, but can be used for other purposes as well.

In principle it is possible to produce chemicals from lignin, instead of from oil or natural gas. However, there are still many hurdles on the road ahead. In the meantime lignin can be used as a (clean) feedstock for power plants.

This only gives an indication of the wealth of possibilities to make use of the substances present in biomass in a more sophisticated way, in order to optimize their use and to reduce the negative effects of our human activities to make a real step forward on the route to a sustainable society.

Third question – sustainable power generation routes

Preferably, electricity must be produced as directly as possible from solar radiation, because this does not directly lead to related mass streams of by-products as is the case when making use of fossil fuels for electricity production. Also, making use of fossil fuels with a much higher speed than they are generated in our natural system leads to depletion and to the release of combustion products at other times and places on earth than where the fossil fuels originally came from. This has all kinds of negative effects e.g. emission of greenhouse gases, production of acid rain, and fertilization of soil and water, often leading to a decrease in biodiversity.

At present, the most common silicon-based photovoltaic (PV) cells on the market have an electric efficiency of about 11%, their production leads to a severe environmental load, they are relatively expensive, and they produce only electricity when day light is available. Ongoing research on e.g. lowering production costs and increasing the efficiency of light absorption and energy conversion could, however, improve the prospects for PV in the long term.

The production of a “free” electron from solar radiation in the visible (for human beings) part of the spectrum has a much higher efficiency, and research focused on imitation of this process can lead to a much more efficient electricity production combined with a very much lower impact on our natural environment. One remark is of importance when harvesting solar radiation in order to avoid the environmental impact of this process: the optical characteristics of the surface (e.g. a dark roof or façade) before covering this surface with PV cells and those of the surface covered with PV cells must be homogeneous. Otherwise, changes in emission and reflection of light and heat upon the surfaces covered by PV can lead to changes in climatic conditions.

In case biomass is used, it is important to use it according to what was said above in the answer to the second question. The highest energy efficiencies can be obtained when a Combined Cycle Power Plant (a combination of a gas turbine and a steam turbine) is used. This is only possible when the combustion gas is clean and has a maximum temperature of about 1500K, directly after the so-called combustion chamber. It is furthermore of importance that the fuel for this process is produced from biomass such that the overall exergy losses in this production process are small. A good example is a mixture of ethanol and water obtained from the sugar monomers obtained after fermentation from biomass. An advantage of this mixture is the high energy density compared to gaseous fuels. A disadvantage is the large energetic cost of transporting a liquid over larger distances through pipelines compared to the transportation of a gas over the same distance. When using a Combined Cycle Power Plant, however, the gas and steam turbines must be large enough to reduce the negative influence of gas (or steam) leakage, from the high-pressure side to the low-pressure side, which does not contribute to power generation. To give an idea: the power output must be in the order of 1 MW or larger. At higher power outputs more turbines can be used, making it possible to repair a turbine and to still produce enough electricity.

Theoretically, fuel cells can have higher efficiencies than the above-mentioned power plants. At the time of writing, further development is necessary to enhance the efficiency but, even more important, also to improve their reliability and, related to this, their operational lifetime. Hydrogen and methane are used as fuel in fuel cell systems nowadays. The use of methane obtained from anaerobic fermentation of biomass, as fuel for an improved fuel cell system, can be a good option for the campus in the future – either before much better PV cells enter the market or in combination with PV cells. Fuel cells are built in a modular manner so they can be reasonably well scaled up to a larger power output.

The options mentioned so far have, or can have, relatively high energy-efficiencies. From that point of view a larger (much larger than the electricity demand of the campus) scale power plant using a biomass feed of ethanol and water, in combination with a biomass refinery, is a good option in the near future. This, however, is too large for Xperience Parkstad.

Other types of power plants fuelled by biomass have (much) lower efficiencies when one looks at the production route from biomass to electricity. The simplest possibility is direct combustion of biomass. This case was already discussed in the answer to question 2. A point not yet mentioned is that biomass can contain a lot of water and its presence may lead to the impossibility to ignite the biomass. When combustion is possible, the presence of water leads to lower combustion temperatures and consequently to a lower energy efficiency of the power plant. In these cases drying can be used, although it comes at energy and financial costs.

An example of a more complicated route is to first produce synthesis gas (syngas), which needs an exergy input. After the conversion of a mixture of carbon mono oxide with water into carbon dioxide and hydrogen (the so called shift reaction), followed by separation, hydrogen can be obtained that can be used as fuel in a fuel cell power plant. Synthesis gas can be used as fuel for a combined cycle (gas and steam turbines) power plant. Hydrogen and synthesis gas are clean fuels, unlike biomass itself, and lead to higher energy efficiencies of the power plants. At this moment the overall energy efficiency is in the order of 50%. As is to be expected, the financial costs of power plants fired by syngas or hydrogen are much higher than those of the power plant only, in view of the need to first produce the fuels from biomass.

In other biomass treatment processes to produce cleaner fuels, e.g. pyrolysis and hydro thermal upgrading, biomass is heated to mainly produce solid carbon, oil, and a gaseous product. In the newer versions of the pyrolysis process, the oil is seen as an important product that can be separated in different fractions serving different purposes. Often the carbon is combusted and part of this thermal energy is used for the pyrolysis process. The remaining part of the thermal energy from carbon combustion and the thermal energy obtained from the combustion of the gaseous product is used to produce steam that can be used to drive a steam turbine/generator to produce electricity. In these cases the energy efficiency whereby electricity is produced is in the order of 30%.

It was mentioned above that biomass-fired combined cycle power plants should have a minimum power output of about 1 MW to be reasonably efficient, while the power needed by the campus is about 2 MW. The most efficient power plants are those with the highest power output on the market, but having such a large power plant in the campus would entail a considerable power surplus, since the campus demand for electric power is actually close to the minimum output of commercially available power generation installations. Such a surplus could be handled by delivering large amounts of power to the grid, but such larger power plants would cause too large a burden for Xperience Parkstad and are too far away from its core business. However, being a partner in a larger project, participating in the realization of such a power plant in the region can be a good option – although it is not a solution on a relatively short term to make the power supply system of the campus much more sustainable. One of the consequences of the realization of a sustainable society is that on the smallest human scale the interaction with the direct environment must be as sustainable as possible. From this point of view, and given the wish of Xperience Parkstad to make the energy supply system much more sustainable on short term, an own solution has to be the main goal, but of course cooperation with others nearby to realize such a power supply system has to be explored further.

The best options for Xperience Parkstad in the future are those that can be built in a modular way such as PV and fuel cell systems. This means that the power to meet Xperience Parkstad needs can be generated on its campus. A disadvantage of PV cell systems is that they only produce electricity when solar radiation is available. Thus storage is needed. One option is to use batteries. Although batteries have been improved during the last years, many cells are necessary; they are expensive and have a relatively short lifetime.

Because electricity is also needed at night, storage facilities are required. Two of the possibilities are: storing as potential energy by pumping up water in the gravity field of the earth to a larger height, or storing as chemical exergy in substances such as hydrogen and oxygen obtained by electrolysis of water. In the first case an elevated water storage facility and a turbine are needed, and in the second case either a fuel cell system or a power plant based on combustion of hydrogen with oxygen. It is also possible to deliver the extra power produced during daylight to the grid and to import power from the grid when no, or not enough, solar radiation is available.

The best option on the short term is to produce methane from biomass by anaerobic fermentation and to combust this in a gas motor/generator combination to produce electricity and heat. These gas motors/generators are on the market for a wide range of power outputs and efficiencies. The electric efficiency is in the order of 30% but in principle also the exergy content of the leftovers of the digester should be included in the overall efficiency of the process, because these leftovers can in principle be used to return the minerals (from the biomass and organic material) to the soil from which the biomass had been harvested.

4.2.5 Conclusions

This section presented and discussed information about exergy supply needs by Xperience Parkstad, now and in a future scenario of appropriate building related measures to reduce energy demand substantially. The primary focus is to achieve a sustainable campus and to integrate the educational programmes of the four different Education Institutions cooperating in Xperience Parkstad, in order to realize a more personal, student-oriented education.

Based on this information it is possible to consider Xperience Parkstad as a basis for benchmarking. The intention is to develop all aspects of Xperience Parkstad to realize complete sustainability, as fast as financial means will allow.

The COSTeXergy action provided input to this process by addressing three questions to its Work Package 2 members, and working them out as far as allowed by available information. In short, the answers to these questions are:

- integration with the Mine Water System (MWS) is possible and desirable, especially since only low temperature heating and high temperature cooling are to be applied after the necessary improvements of the building envelopes.

- improving the exergy performance of existing buildings is more complex and costly than building new exergy-efficient real estate. In the short to mid term, power generation offers realistic prospects for enhancing campus sustainability.

- at present, a sustainable option for power generation is to use anaerobic fermentation to produce a gas mixture of mainly methane and CO_2 that can be used to fire the power plant, and to return the leftovers of the digester (containing most of the minerals taken up by the plants etc. and organic material) to the soil on which the biomass had grown. A drawback is the relatively low efficiency for electricity production for the rather small-scale power plants with a power output matching the campus demand. Later, biomass rectification and possibly further treatment can produce ash-free fuels that can be used for power generation with much higher efficiencies.

- at this time we can expect that in the not too far future there will be two options for producing electricity in relatively small modules, which makes it easy to produce electricity from very small up to very large scales. In this way it will be simpler to build a power plant with a power output complying with the demand of the campus. These options are PV cells and fuel cells, both with substantially higher efficiencies than at this time. As for the fuel cells, they must be much more reliable first.

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4.3 Quasi-steady variation of exergy balance of traditional and low-exergy detached houses in heating period

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4.3.1 Introduction

Exergy analysis can give us a tool to lower the loss of exergy, which can be understood as that part of the exergy flow which really disappears upon utilization and becomes unavailable for subsequent use (Szargut, 2005). For many years exergy analysis has been used in different fields of industry e.g. metallurgy, power plants, etc. (Szargut, 2005). In recent years this method has found more and more recognition and application, also in the built environment. For the purposes of this book, more detailed working definitions of exergy and low-exergy are presented in Chapter 1.

An excel-based Exergy calculation sheet (version 7.7) was developed over a few years at the IEA ECBCS Annexes 37 and 49 for steady state calculations for heating, Schmidt and Shukuya, (2005) and Schmidt (2004).

This paper shows results obtained by using the excel tool to estimate energy and exergy flows in a traditional and in a low-exergy (low-ex) residential building over a heating season. Calculations were made only for the thermal part of exergy, in Poland, where the rather cold climate leads to a negligibly small error caused by not taking into account the humid air exergy (Sakulpipatsin, 2008). The monthly average outdoor temperature is used as a reference temperature so that the calculation reported in this paper can be assumed quasi-steady.

4.3.2 Aim of investigation

The investigation was aimed at:

- performing quasi-steady calculations of the energy and exergy supply and demand in a heating season;
- using exergy analysis to calculate and discuss the actual processes linked to energy and exergy balances in residential buildings, based on an example consisting of two detached houses: a traditional and a low-ex one;

- analyzing case studies of energy and exergy flows for different building technologies and heating systems;
- searching for possibilities to choose the best solution among different heating and ventilation systems in buildings.

4.3.3 Traditional and low-exergy houses

In old dwellings the annual demand for space heating is about 200 kWh/m^{2}year, and in newly-built dwellings it is about 90 kWh/m^{2}year. In buildings made using the so called low energy technology, this demand is about 30% lower. It is also well known that for passive buildings the demand should be 15 kWh/m^{2}year.

Such a big difference in heating energy demand is of course technology-dependent, and there is continuous progress in technology for building materials, heating, cooling and ventilation devices.

In Polish weather conditions, supplementary active heating systems are used during the periods when outside temperatures are lowest. Strictly speaking, this does not meet the passive house conditions established by the Passive House Institute in Darmstadt about fifteen years ago. In this sense, this paper uses the term ‘low-exergy’ (or ‘low-ex’) house proposed by IEA-ECBCS Annexes 37 and 49 (Schmidt and Shukuya, 2005 and Schmidt, 2004), to designate the house whose building parameters correspond to Passive House regulations.

4.3.4 The traditional and low-exergy single family houses under consideration

A traditional and a low-ex detached houses, located near Olsztyn (north-east of Poland), are analyzed in this paper; weather conditions for this location are assumed in the calculations. The basic building parameters of both houses are the same, as given in Table 1. The standard outdoor design temperature is -22°C.

The construction of the low-ex house is made according to the passive house regulations, and especially the thermal transmittances U of the building elements are appropriately chosen.

Superinsulation is employed to significantly lower the heat conduction through the house envelope, where insulation layers are 30-44 cm thick. The house is made of gravelite-concrete prefabricated walls, and thermal bridges have been minimized as much as possible.

The traditional house is based on a similar design as the low-ex house, the difference in construction lying in the materials (and hence the thermal transmittance) of the building envelope as shown in Table 2 — the average Ui values for the traditional house are almost twice as high as for the low-ex house.

Volume (heated)	456 m^3
Net floor area	153,3 m^2
Indoor air temperature	20 ºC
Exterior air temperature	- 22 ºC
Number of occupants	4

Table 1: Overall data of traditional and low-ex detached houses

	Thermal transmittance Ui [W / (m²*K)]	
Building part	*Low-ex house*	*Traditional house*
Exterior wall	0,10	0,37
Window	0,60	1,00
Door	0,80	1,40
Roof	0,11	0,27
Floors to ground	0,13	0,22

*Table 2: Thermal transmittance U_i [W/(m^2*K)] in low-ex and traditional houses*

	Window areas [m²]	
Location	*Traditional*	*Low-ex*
South	12,55	25,46
North	3,25	8,47
Other	2,15	8,47

Table 3: Window areas and orientations in traditional and low-exergy houses.

The biggest differences can be found in window areas. The idea of passive building (applied to the low-ex house) requires attention to window areas and locations, as shown in Table 3.

The low-ex single house is equipped with mechanical ventilation including a heat recovery system. For domestic hot water (DHW), heat-pump assisted vacuum solar heat collectors are used. A system of ground heat exchangers (GHE) is also provided. The temperature of supply air blown at the GHE outlet is assumed to be about 5 ^{0}C. An air-air heat pump is also installed in the building, and the ground heat exchanger pre-heats the air supplied to the heat pump. There are also a heat recovery device and an electrically heated water storage tank, for the periods when the outside temperatures are lowest.

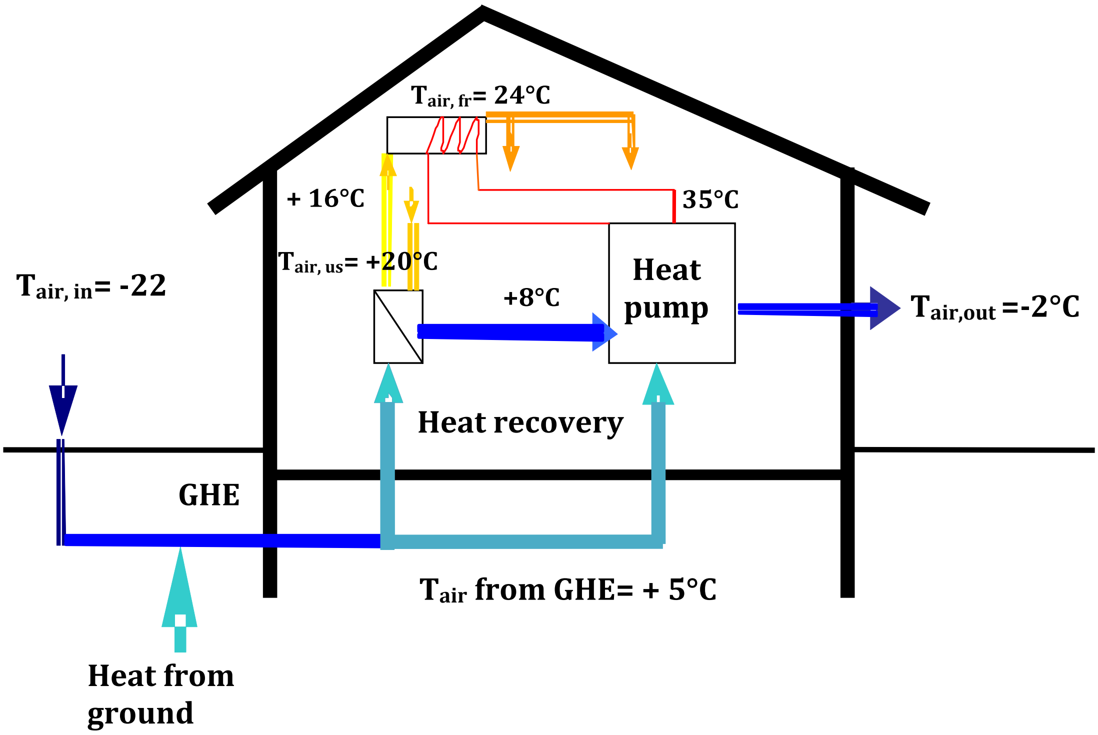

Figure 1: Heating system in low-ex house

In the traditional building, only natural ventilation is assumed. There is a gas condensing boiler for heating and DHW, equipped with conventional plate heat exchangers.

4.3.5 Results of exergy calculations for the heating season

The calculations of energy and exergy balances were done by using the Excel sheet (version 7.7) prepared by IEA ECBCS Annex 37 and improved in Annex 49, (Schmidt and Shukuya, 2005). Monthly average outside temperatures were used for Olsztyn-PL during a heating season from October (month X) until March (month III), for the calculation of energy and exergy flows in the traditional and low-ex houses. Values of average outside temperatures are shown in Table 4.

Months		Average temperatures [°C]
October	*X*	+6,3
November	*XI*	+1,9
December	*XII*	-0,5
January	*I*	-3,6
February	*II*	-2,9
March	*III*	+2,5

Table 4: Average outside temperatures

The heating system for both the traditional and the low-ex houses is divided into seven parts: primary energy transformation, heat generation, heat storage, heat distribution, heat emission, room air and building envelope. For each of these parts, the energy and exergy flows are calculated considering the different envelope constructions and heating-system elements mentioned above. Figures 2 and 3 show the results of exergy supply and demand during the heating season for both houses. In both figures, the symbols T and P stand for traditional and low-ex (passive) single house. The roman numerals correspond to the month numbers, as shown in Table 4.

The figures show that the heating season is much shorter for the well-insulated low-ex house *P* than for the traditional house *T*. In the months October (X) and March (III), exergy demand of the low-ex house is very small, and mainly due to heat losses through the building envelope (Fig. 3). This exergy demand can be met by internal heat gains in both months, plus a small amount of solar gains through windows in March (Fig. 2). From the months November (XI) to February (II), a renewable energy part also appears in the exergy supply, due to the use of the ground heat exchanger and of the larger window surface area in the case of the low-ex house (P). The solar radiation gains are twice as high for the low-ex house compared to the traditional house. The heat losses through the building envelope are twice as high for the traditional house than for the low-ex house. In the traditional house (because of the natural ventilation) there is no electrical energy demand for ventilation, which was accounted for in the low-ex house. On the other hand, thermal exergy losses due to ventilation are much higher for the traditional house than for the low-ex house, where ventilation air heat recovery is applied besides the ground heat exchanger.

Assuming the same number of occupants, the internal heat gains from electrical appliances and from residents are the same for both houses.

Figure 3 shows exergy demands for the traditional and low-ex houses, for each month of the heating season. For the traditional house, the greatest exergy demand is connected to the heat generation process, which is much smaller in the case of the low-ex house. For the low-ex house, the greatest exergy demand is connected with the primary exergy transfer. For both kinds of houses big exergy losses take place during primary energy transformation.

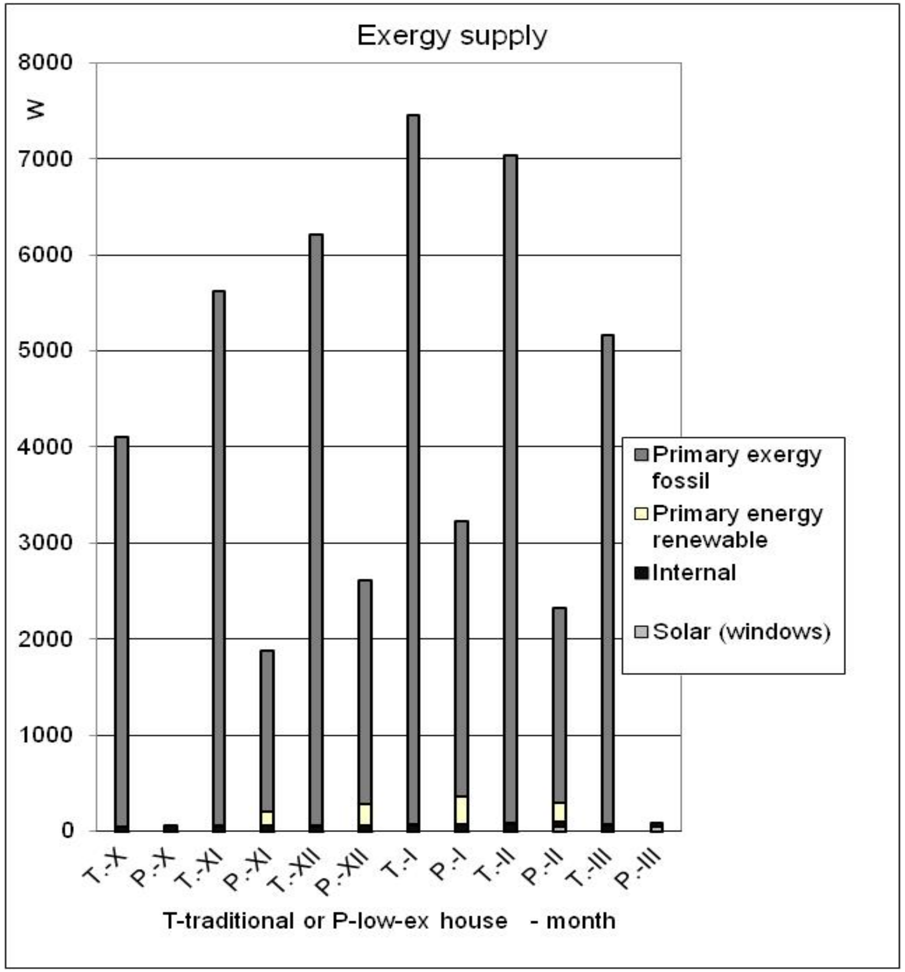

Figure 2: Exergy supply during the heating season for traditional (T.) and low-ex (P.) houses

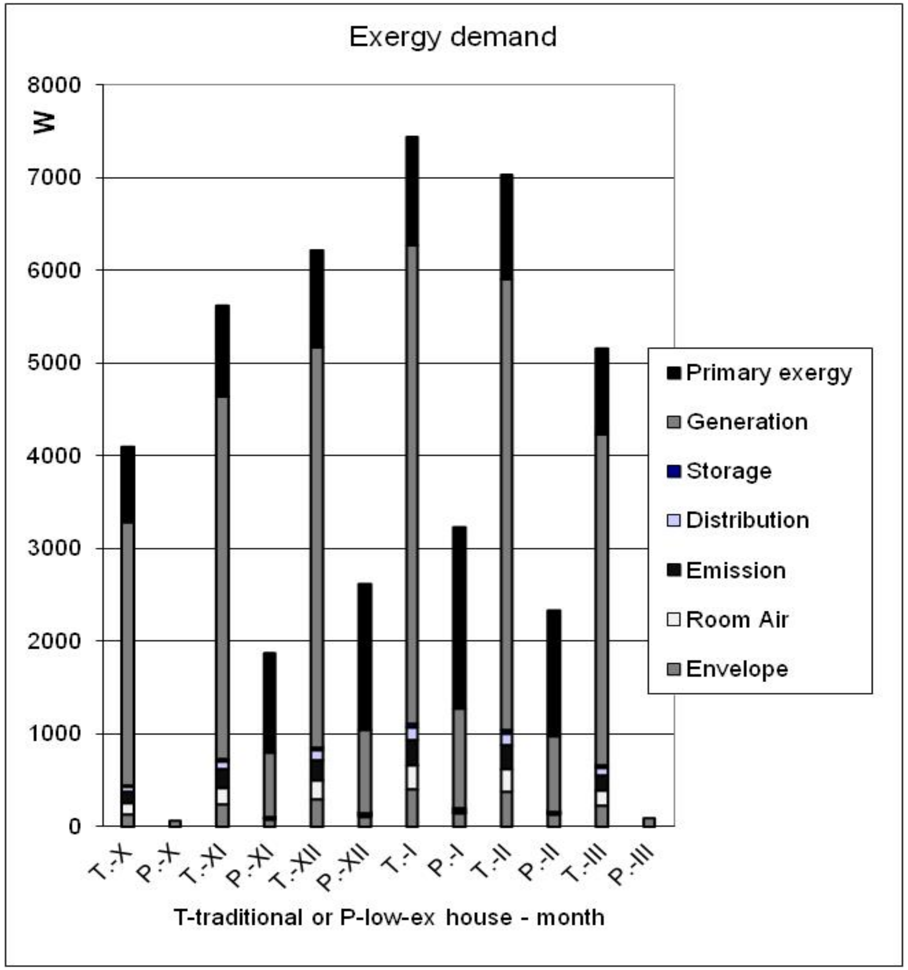

Figure 3: Exergy demand during the heating season for traditional (T.) and low-ex (P.) houses

The biggest values of exergy supply and demand are for January (I), when the average outside temperature is the lowest.

4.3.6 Conclusions

This section presented an analysis of seasonal thermal exergy supply and demand, for a cold climate in Poland near Olsztyn, for a low-ex and for a traditional single family house. Calculations were made by means of an Exergy spreadsheet (Version 7.7) developed by IEA-ECBCS Annexes 37 and 49. It is assumed that in this cold climate the thermal component of exergy prevails and the error made by neglecting the humid air component of exergy is rather small. The monthly average outdoor temperature was taken as the reference environment and the pressure change between indoor and outdoor environment was not considered, but solar radiation was included. Because average outdoor temperatures were taken over relatively long periods, on a monthly basis, these calculations can be called quasi-steady.

For the low-ex house, the heating season is about two months shorter, and for the traditional house the total heat demand is about two times higher.

Heat losses through the building envelope are approximately 50% higher for the traditional than for the low-ex house. In turn, average electricity demand for ventilation in the low-ex house is higher (112W).

In both buildings, the biggest exergy losses take place during heat generation, mostly due to the water boiler. For the traditional building, these losses are about 6 times bigger than for the low-ex house. In the low-ex house the use of renewable energy is higher than in the traditional house, due to heat gains from the soil (through the ground heat exchanger) and from solar radiation (through windows).

References

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Nomenclature

U_i	Thermal transmittance [W/m^{2}K]
T	Air temperature [°C]

Subscripts

air	Air
fr	fresh
in	inlet
out	outlet
us	used

Abbreviations

DHW	Domestic hot water
GHC	Ground heat exchanger
T.	Traditional house
P.	Low-exergy house

4.4 Optimization Strategies and Best Practice Case Study: an Exergy Approach

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4.4.1 Introduction

In mild climates like Po Valley in North Italy, where the winter temperatures are such that the number of degree days is around 2300, the usual period for heating buildings is six months (from mid October to mid April). Usually heating is supplied for a limited time of the day, i.e. usually the systems are switched on for 14 hours over two or three periods. Moreover, these locations (especially the town centres) contain a large number of historical buildings which cannot be insulated. Furthermore, the retrofit of the buildings and/or of the HVAC systems entails several practical problems. For these purposes, research has been carried out in order to check if the heating system may allow energy and costs reductions.

This work is based on a study about improving the energy efficiency upon renovation of a poorly insulated building, by substituting the heat generation system. In this section, different aspects are considered concerning both the building envelope and the heating systems, including operating strategies for different heating fuels. Current analysis based on the primary energy concept is then compared with exergy analysis.

4.4.2 A case-study of retrofitting existing buildings

The work is based on a real building retrofitting case, whose main results are summed up in this section. The case-study is described in detail in De Carli et al. (2007). They retrofitted a number of buildings in Gallarate (North of Italy) by changing the heat production system and the heating strategy, without working on thermal insulation. An audit based on measurements was set up to evaluate the energy consumption, based on TRNSYS (The University of Wisconsin, 2012) simulations in order to reproduce the energy savings obtained in the case-study. TRNSYS stands for TRaNsient Systems Simulation**.** The monitoring campaign and the modelling allowed an efficiency curve to be fitted to the traditional boiler used in these analyses.

Both the insulation and the heating system affect the energy use in buildings. This work focuses on the effect of intermittent and continuous operation of the heating system, considering not only the building envelope, but also the efficiencies of emission, distribution and heat production of the heating systems.

When looking at the possible heat production systems, it might be useful to underline the following observations:

- for a given heating demand, running the heating system over longer time periods allows working at temperatures closer to room temperature;
- running the heating system over longer time periods also allows lowering the peak heating loads, and hence sizing the system for a lower capacity;
- in line with the previous point, systems which work continuously can be undersized and can work with higher load factors (i.e. ratio between average power of the system and design power).

The first point implies that continuous operation could improve the efficiency if the water temperature decrease entails a rise in the heat production efficiency. This happens in condensing boilers, where lowering the heat production temperature improves the efficiency of the system (figure 1.A). The same trend is shown for a heat pump (figure 1.B). In this case, it might be seen that the heating capacity of a heat pump also influences the COP.

A **B**

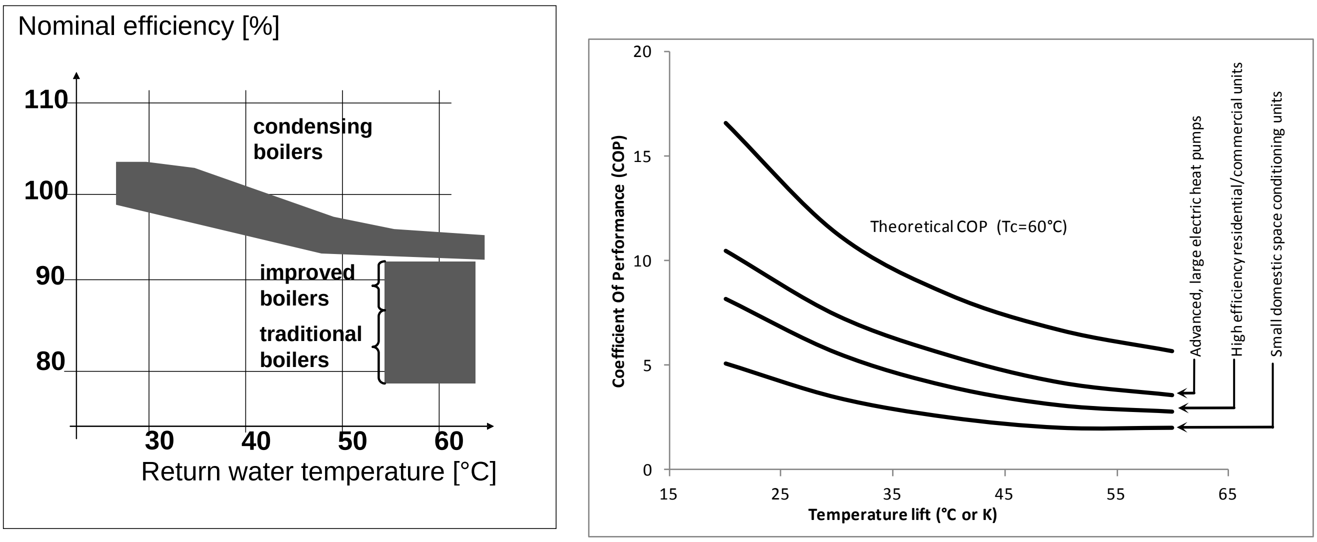

Figure 1: Nominal efficiencies related to operating temperatures for heating purposes: boilers (A) and heat pumps (B), De Carli et al. (2007)

Hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Mode 1	OFF					ON				OFF						ON							OFF	
Mode 2	OFF					ON				OFF			ON			OFF		ON				OFF		
Mode 3	Set Back					ON																Set Back		

Table 1: Investigated cases in a residential building in the North of Italy.

As described in De Carli et al. (2007) the heat production efficiency can increase if the load factor increases. This can be seen in figure 2, where intermittent operation is compared to continuous operation for the same building. In the same paper a residential building (a reference stock building in Italy) was considered and three cases were investigated as shown in Table 1: mode 1 (three off periods), mode 2 (two off periods), mode 3 (set-back overnight).

From measurements and dynamic simulations, different operating conditions are evaluated. Table 2 shows the energy results. From table 2 it becomes apparent that the net energy demand of the building is lower if the number of working hours is limited. It could also be the case that the relevant factor is the set-point temperature instead of the number of periods the system is not running.

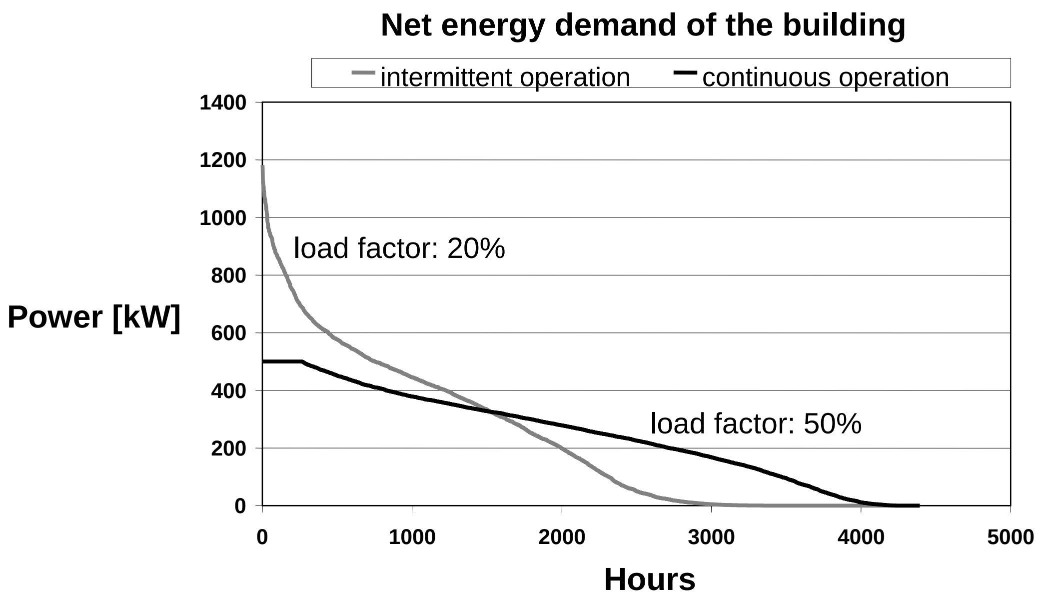

Figure 2: Frequency curves in the case of continuous and intermittent operation

	Intermittent Set-point 20°C (Mode 1)	Intermittent Set-point 20°C (Mode 2)	Intermittent Set-point 22°C (Mode 1)	Intermittent Set-point 22°C (Mode 2)	Day time Set-point 21°C (Mode 3)
Heating power peak [W/m³]	39	38	44	43	19
Net energy of the building [kWh/(m²y)]	97	98	114	115	122
Deviation on net energy compared to last case [%]	- 20	- 20	- 7	- 6	-

Table 2: Comparison between peak loads and energy demand in intermittent modes and set-back mode (last column), De Carli et al. (2007).

The net energy demand is important, but the energy consumed in a building is related to both the overall performance of the building and to the system, i.e. heat emission, control, distribution and generation efficiencies have to be added. It has to be underlined that new buildings, due to regulations which impose good insulation, have lower deviations in net energy demand when working at constant temperatures (or with set-back temperatures close to day-time temperatures) compared to intermittent operation. Further details on the analysis and results of the case study can be seen in De Carli et al. (2007).

Based on these considerations, it can be observed that uninterrupted operation, or a set-back temperature close to daytime temperature can be interesting in retrofitting heating systems. In existing buildings, radiators work with relatively high temperatures. If the system is replaced by modulating condensing boilers, radiators can work at lower temperatures for longer periods of time. The resulting condensation allows higher heat generation efficiencies.

Running with lower temperatures also influences distribution and emission performances of the heating system. This leads to a combined efficiency of about 91% in the case of set-back operation and 86% in the case of intermittent working.

De Carli et al. (2007) notes that savings of about 28% in gas consumption, compared to old boilers, are possible in retrofitted buildings where condensing boilers run for longer time periods and at lower temperature levels. These savings regard both the net energy demand and the losses of the heating system (generation, distribution, emission and control efficiencies). It has to be noted that buildings where the heating system runs over longer periods of time present higher average temperatures. Therefore, maintaining the same indoor mean conditions would lead to a saving of 43% as shown in table 3. These results do not consider the possible improvement by introducing control systems, e.g. thermostatic valves which may further reduce the energy consumption.

Heating strategy	**Energy need of the thermal plant [MWh]**	**Natural gas consumed [Nm^3]**	**Energy saving [%]**	**Mean heat production efficiency on the whole season [%]**
Post-operam Set-Back Mode	1095	112600	-	101
Ante-operam; two intervals with 20°C set point	871	155550	28	58
Ante-operam; two intervals with 22°C set point	1024	197270	43	54

Table 3: Summary of the results of the case-study analysed in De Carli et al. (2007).

4.4.3 Analysis of energy saving by means of lowering supply temperatures in existing and new buildings

Different heating strategies are simulated with TRNSYS to determine the net energy demand. Next, the EN 15316-2-1 (2007) and EN 15316-2-3 (2008) procedures are implemented to consider the efficiencies of the emission, control and distribution systems. Afterwards, the heat production efficiency is evaluated based on experimental curves derived from the monitoring campaign of the previously mentioned case-study.

The analyzed building typology is rather simple: the main characteristics are summed up in table 4, where two possible levels of insulation are considered.

Characteristics				
30 m x 10 m, 4 floors, 12 m total height		Two heated zones (with the same heating strategy) and one non-heated (the staircase)		
Total heated surface = 1100 m^2		Unheated surface = 100 m^2		
Heated Volume = 3300 m^3		Unheated volume = 300 m^3		
40 m^2 transparent surface for each orientation		Internal gains according to EN 13790		
ACH (Air Change per Hour) = 0.5 Vol/h				
Thermal transmittance				
Not-insulated building	U_{Wall} = 1.0 W/(m^2 K)	$U_{Unheated}$ = 0.65 W/(m^2 K)	U_{Window} = 5.8 W/(m^2 K)	$U_{GroundFloor}$ = 0.7 W/(m^2 K)
Well-insulated building	U_{Wall} = 0.2 W/(m^2 K)	$U_{Unheated}$ = 0.27 W/(m^2 K)	U_{Window} = 1.4 W/(m^2 K)	$U_{GroundFloor}$ = 0.36 W/(m^2 K)

Table 4: Building characteristics.

The design load is estimated by means of TRNSYS assuming no solar radiation and no internal gains. The building is simulated in the climate of Venice (Italy), based on the Energy Plus Weather file. Three different strategies of operating various heating systems are considered as shown in tables 5 and 6.

Mode	Set point Temperature [°C]	Working time [h]	Turning off time [h]
Intermittent	21	6:00-21:00 from Monday to Sunday	0:00-6:00; 21:00-24:00 from Monday to Sunday
Continuous	21	All the day, from Monday to Sunday	-
Set-Back	21 (a) – 19 (b)	(a): 6:00 – 21:00; (b): 0:00 – 6:00 and 21:00-24:00 from Monday to Sunday	-

Table 5: Different heating system operation strategies

First Letter (Regulation System)	U: unregulated system or with central supply temperature regulation; C: control system with master room space P-controller (2 K)
Second Letter (Heat Emission System)	*R*: radiators; *F*: dry floor heating system; *C*: ceiling heating system; *W*: wall heating system
Third Letter (Heating Strategy)	*I*: intermittent mode; *C*: continuous mode; *S*: set back mode
Fourth Letter (Heat Production System)	*T*: traditional boiler; *C*: condensing boiler; *H*: heat pump
Example: Base Case URIT	Unregulated radiator emission system, (or with central supply temperature regulation); intermittent heating mode and traditional boiler
Example: Case 4 CRSC	Radiator emission system, with master room space P-controller (2 K); set-back mode and condensing boiler
Example: Case 9 CFSH	Dry floor system with P-controller; set-back mode and heat pump

Table 6: Legend of the different heating systems and operation strategies implemented in the analyses.

According to EN 15316-2-1 (2007) the design temperatures are assumed to be: T_{supply} = 90°C, T_{return} = 70°C for the intermittent and set-back mode; T_{supply} = 55°C, T_{return} = 45°C for the continuous mode. During the analysis, the mean temperature of the system is calculated and used to determine the thermal losses. The radiators are placed on the outer walls. The detailed method described in EN 15316-2-3 (2008) is implemented with the assumptions made in Annex A of the same Standard.

4.4.4 Results

The results for the different cases are reported in table 7: the per cent deviation of the Specific Primary Energy (SPE) is summarized with reference to the SPE of the Base Case; the design loads and their per cent variation with respect to the Base Case are reported for each solution.

	Not-insulated building						Well-insulated building					
Case	SPE [kWh/(m^2 y)]	% SPE ref. BC**[%]	Design Load [kW]	% PL* ref. BC [%]	produced CO_2 [kgCO2/(m ^{2}y)]	% CO_2 ref. BC [%]	SPE [kWh/(m^2 y)]	% SPE ref. BC** [%]	Design Load [kW]	% PL* ref. BC [%]	produced CO_2 [kgCO2/(m^2 y)]	% CO_2 ref. BC [%]
BC URIT	180	-	132	-	45	-	42	-	70	-	11	-
1 CRIT	170	94	132	100	43	95	40	95	70	100	10	96
2 CRIC	115	64	132	100	29	64	27	64	70	100	7	65
3 CRCC	126	70	70	65	32	70	28	67	35	50	7	67
4 CRSC	116	64	85	65	29	65	25	60	50	71	6	59
5 CRSH	111	62	85	65	27	60	29	69	50	71	7	67
6 UFSC	123	68	85	65	23	51	24	57	50	71	6	57
7 CFSC	104	58	85	65	20	43	20	48	50	71	5	48
8 UFSH	76	42	85	65	16	35	12	29	50	71	3	29
9 CFSH	61	34	85	65	12	27	10	24	50	71	2	23
10 UCSC	130	72	85	65	33	72	25	60	50	71	6	60
11 CCSC	111	62	85	65	21	46	22	52	50	71	5	52
12 UCSH	80	44	85	65	20	44	13	31	50	71	3	30
13 CCSH	65	36	85	65	16	35	11	26	50	71	3	25
14 UWSC	128	71	85	65	32	71	25	60	50	71	6	60
15 CWSC	109	61	85	65	28	61	22	52	50	71	5	52
16 UWSH	87	48	85	65	22	48	14	33	50	71	3	32
17 CWSH	70	39	85	65	17	38	12	29	50	71	3	27

*Table 7: Results of the analyses, *PL: Peak Load, **BC: Base Case.*

4.4.5 Discussion

Energy

Regarding the cases with radiators (BC vs. case 5 CRSH), the control system influences the Specific Primary Energy (SPE demand of ±7% with reference to the BC). The substitution of the 'traditional' boiler with a modulating condensing technology coupled with a good control system, results in an SPE saving of about 36% maintaining the intermittent mode heating strategy. Very similar results are obtained by programming the heating system with the set-back mode. However, it has to be noted that the latter solution provides a higher level of comfort. The continuous operation mode coupled with a condensing boiler provides high energy savings (about 30% with reference to the BC), but programming the heating strategy as set-back appears to represent the best compromise between energy saving and comfort conditions. The substitution of the old generation system with a heat pump maintaining the radiators (i.e. modifying only the heat generation system) and coupled with a set-back mode heating strategy would provide around 35% of energy saving. Although it would allow anyway an improvement compared to the BC, it does not represent the best possible solution. These considerations can be relevant for retrofitting historical buildings where ensuring a better insulation level is not always possible. This work highlights that substituting an old heat generation system with a modern modulating condensing boiler together with a different heating strategy can represent a good solution, when the control strategy allows operating the condensing boiler in the most efficient way.

The control system allows an energy saving of 7-10% with reference to the unregulated solution. A radiant system coupled with a water to water heat pump allows for a reduction of the SPE demand. For radiant systems the savings (cases 9, 13 and 17 in table 7) are higher compared to radiators (Case 4). Table 7 also shows the possibility of reducing the design power by changing to a continuous or set-back mode instead of an intermittent one. As previously highlighted, this allows for a better working of the condensing boiler and the heat pump.

CO_2

Concerning the CO_2 emissions in old buildings equipped with radiators, the installation of a modern condensing boiler or a heat pump leads to a substantial reduction. This amounts to 35% for condensing boilers in intermittent mode, 38% in set-back mode and 32% in the continuous mode, while it reaches the 40% with a heat pump.

Exergy

For the exergy analysis several cases are evaluated. In table 8 a general framework of the obtained results in terms of specific exergy demand (SED) is reported.

As can be seen, for exergy reduction the best solution is case 9. Comparing results, it can be seen that for the heat pump solution the per cent reduction of SED is significantly greater when compared to the SPE. This is due to the influence of the cold source in the heat pump generation system.

Case	Not-insulated building				Well-insulated building			
	SPE [kWh/(m^2 y)]	SPE reduction ref. BC* [%]	SED [kWh/(m^2 y)]	SED reduction ref. BC* [%]	SPE [kWh/(m^2 y)]	SPE reduction ref. BC* [%]	SED [kWh/(m^2 y)]	SED reduction ref. BC* [%]
BC URIT	180	-	149	-	42	-	35	-
4 CRSC	116	36	97	35	25	40	22	37
9 CFSH	61	66	26	83	10	76	5	86

*Table 8: Results of the exergy analyses, *BC: Base Case, SED: specific exergy demand*

4.4.6 Conclusion

In figures 3 and 4 Sankey and Grassmann diagrams for primary energy and exergy are shown for some of the discussed solutions. The reported analyses concern the Base Case, Case 4 and Case 9 (traditional boiler, modulating condensing boiler and heat pump). From an exergy point of view, it can be seen that for all cases the net exergy demand of the building itself is very small. In spite of this, the whole exergy efficiency, defined as the ratio of Ex_{room} and the sum of exergy inputs to the system, is low (except for the last case in figure 4). The highest losses are concentrated in the heat generation system. For example, the heat generation exergy loss is about 90% of the whole exergy demand for the traditional boiler, while it becomes about 84% with the condensing boiler and decreases to about 60% considering a heat pump. The heat emission losses contribution in the unregulated case is about 70% of the emission exergy demand; it decreases to about 65% in the controlled system, and to about 45% for the radiant system case. It has to be observed anyway that the absolute amount of both emission and distribution exergy losses is very small compared to the generation losses. The exergy efficiency is about 2.5% in the Base Case, about 4% for Case 4 and about 18% for Case 9.

As can be observed, exergy analysis mainly addresses the energy sources rather than the different control strategies. In fact, the type of heat generation system greatly affects the exergy flow. Exergy analysis can be a good instrument to investigate technologies working at low exergy levels. It can be seen, for example, that the change in the flowchart from figure 4.B to 4.C (or from 4.E to 4.F) is more evident than the change from figure 3.B to 3.C (or from 3.E to 3.F).

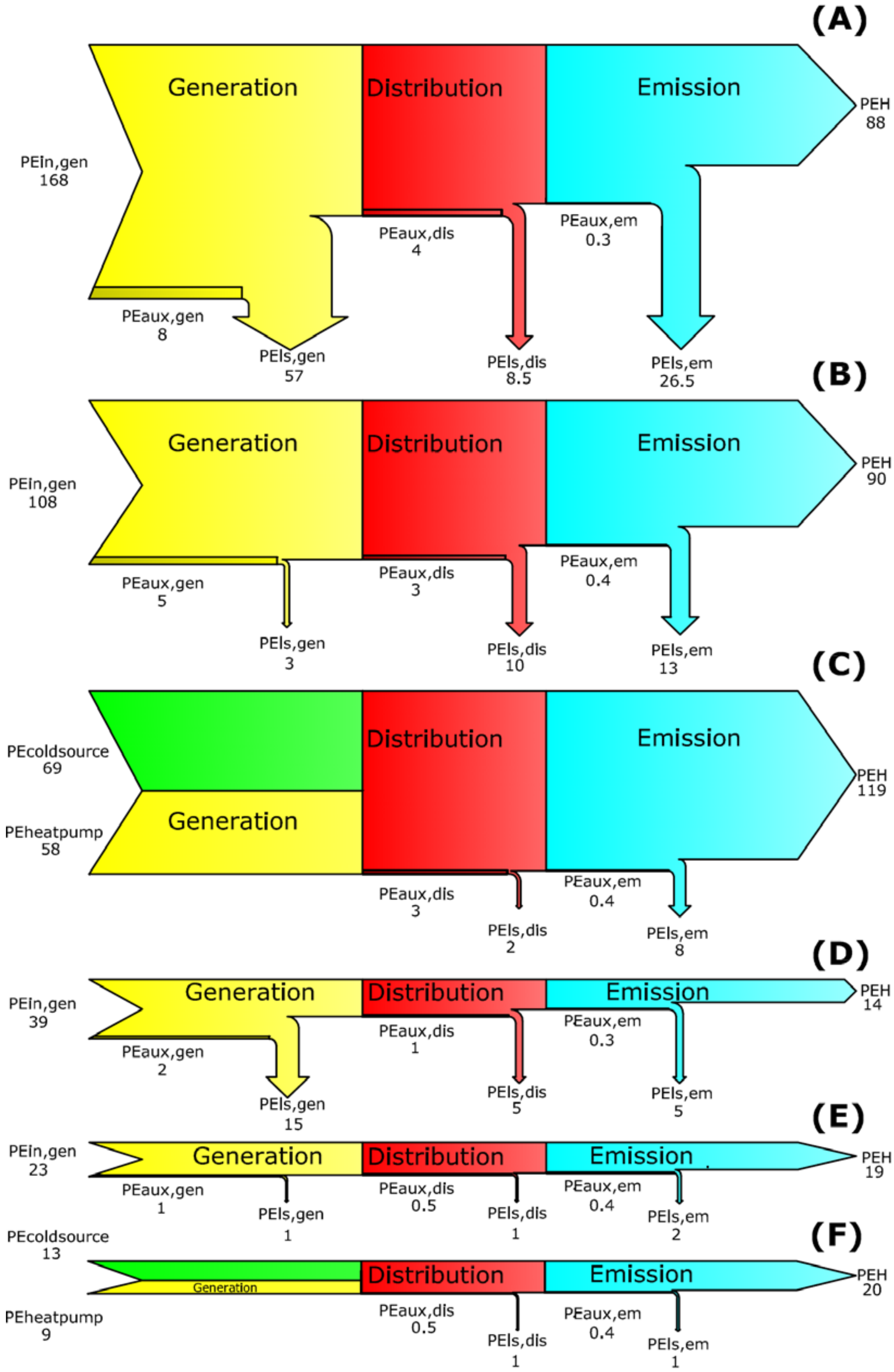

Figure 3: Primary Energy diagrams (Venice weather) for: (A) Base Case URIT - Unregulated radiator emission system, Intermittent mode, Traditional boiler - not insulated building; (B) Case 4 CRSC - Radiator emission system, with P-controller, Set-Back mode, Condensing boiler - not insulated building; (C) Case 9 CFSH - Dry floor system with P-controller, Set-Back mode, Heat pump - not insulated building; (D) Base Case URIT- insulated building; (E) Case 4 CRSC - insulated building; (F) Case 9 CFSH - insulated building. – The amount of Primary Energy fluxes is reported in [kWh/(m^{2}year)] – Scale graphs.

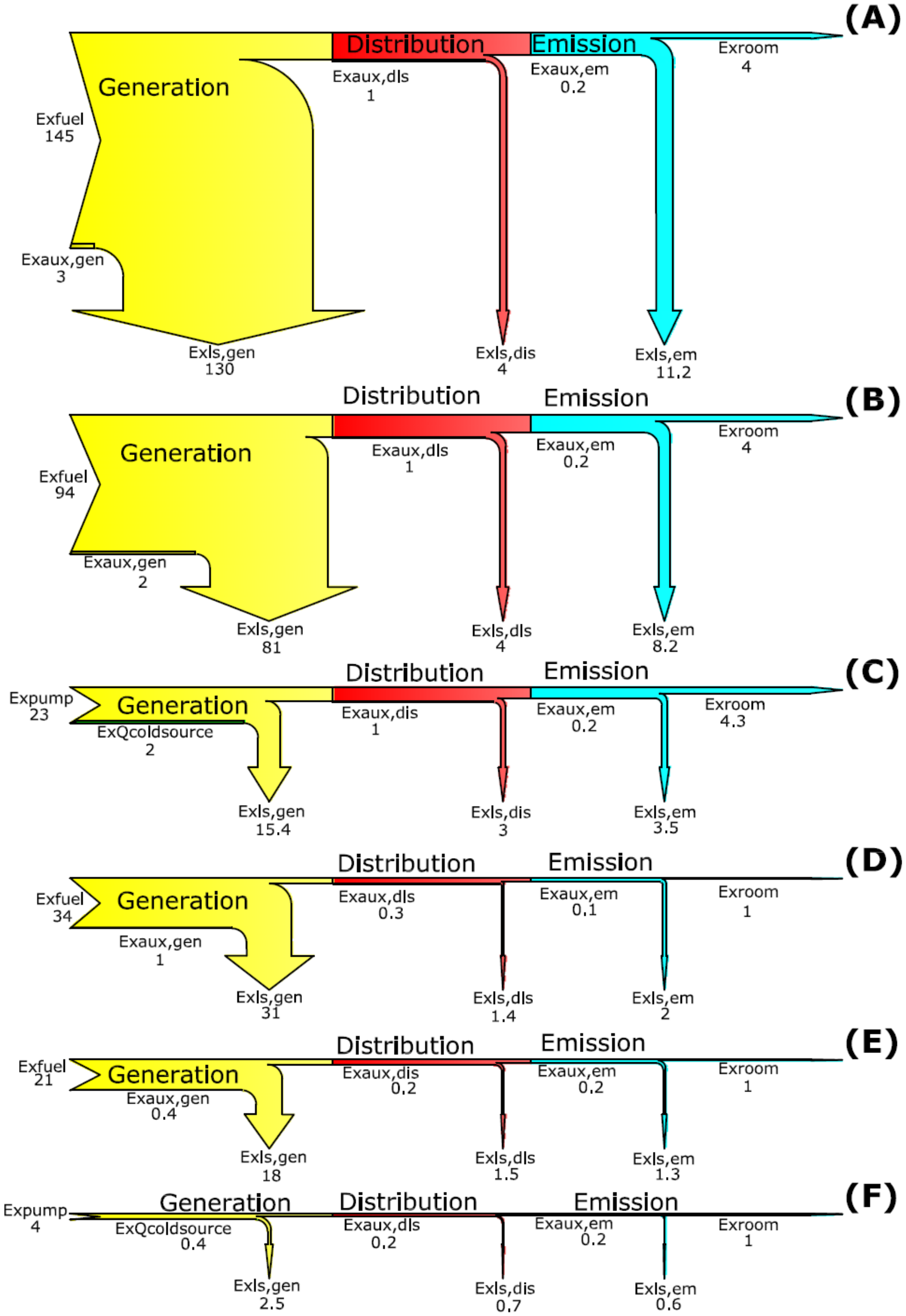

Figure 4: Exergy diagrams (Venice weather) for: (A) Base Case URIT - Unregulated radiator emission system, Intermittent mode, Traditional boiler - not insulated building; (B) Case 4 CRSC - Radiator emission system, with master room space P-controller, Set-Back mode, Condensing boiler - not insulated building; (C) Case 9 CFSH - Dry floor system with P-controller, Set-Back mode, Heat pump - not insulated building; (D) Base Case URIT - insulated building; (E) Case 4 CRSC - insulated building; (F) Case 9 CFSH - insulated building. – The amount of exergy fluxes is reported in [kWh/(m^{2}year)] – Scale graphs.

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Nomenclature

SPE	Specific Primary Energy
SED	Specific Exergy Demand
PEin,gen	Input of Primary Energy to the heat generator (boiler)
PEcoldsource	Energy rate from the Cold Source
PEheatpump	Input of Primary Energy to the Heat Pump generator
PEaux,gen	Primary Energy for auxiliary generation system
PEls,gen	Losses of primary energy related to the heat Generator (boiler)
PEaux,dis	Primary Energy for auxiliary distribution system
PEls,dis	Losses of primary energy related to the distribution system
PEaux,em	Primary Energy for auxiliary emission system
PEls,em	Losses of primary energy related to the emission system

PEH	Primary Energy for heating
Exfuel	Exergy related to the fuel demand for boiler
ExQcodsource	Exergy rate from the Cold Source
Expump	Exergy related to the heat pump
Exaux,gen	Exergy for auxiliary generation system
Exls,gen	Losses of Exergy related to the heat generator (boiler)
Exaux,dis	Exergy for auxiliary distribution system
Exls,dis	Losses of Exergy related to the distribution system
Exaux,em	Exergy for auxiliary emission system
Exls,em	Losses of Exergy related to the emission system
Exroom	Exergy for heating

CHAPTER 5

METHODOLOGIES AND EVALUATION OF HUMAN BODY EXERGY CONSUMPTION

Introduction

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Work on the exergy approach to the design and operation of space conditioning systems (ventilation-heating-cooling) has been growing since the early 1990's, while research on application of exergy analysis to the human heat balance and perception of the indoor environment is more recent.

As buildings are meant to provide a comfortable and healthy environment for their occupants, it is also important to consider their thermal comfort along with the sustainable design and operation of space conditioning systems. From a thermal comfort perspective, it is important to consider the exergy flows both for a building and for the human body.

This chapter introduces a new tool for human-body exergy calculation. Further applications of human body exergy analyses will enable more detailed applications of the tool and better understanding of factors influencing thermal comfort in relation to exergy demand in buildings.

In the first section Shukuya et al. briefly describe their conceptual framework for the human-body exergy balance equation, which they derived from the fundamentals of thermodynamics. This framework includes the key concepts of: wet exergy associated with sweat (which is approximated to liquid water); moist-air wet/dry exergy; warm/cool radiant exergies coming into and going out the human body; and warm/cool exergy transfer by convection. Examples of the whole human-body exergy balance and then the human-body exergy consumption rates for typical winter and summer conditions are discussed in relation to mean radiant temperature, room air temperature, air velocity, and outdoor ambient temperature. A series of recent studies by Shukuya and co-workers shows that there seems to be a set of mean radiant temperature and air velocity giving the lowest human-body exergy consumption rate. Applications also show the importance of warm-exergy exchange between human body and the surrounding wall surfaces in the winter season. In the summer season, consumption of wet exergy contained by liquid water as sweat helps to mitigate the effect of the warm radiant exergy as much as possible; also, cool radiant exergy is maximized by the storage of cool exergy within the walls by nocturnal ventilation or by the use of radiant cooling panels-systems. In a naturally ventilated room space, almost random natural fluctuation of soft air movement (breeze) brings about pleasant coolness, which is a rather dynamic condition different from static neutrality of neither hot nor cold. It is interesting that the lowest values of exergy-consumption rate lie just below a line representing the condition at skin-wettedness of 0.25, over which the human body is not tolerant. These findings support the development of low-exergy space heating and cooling systems.

A further application of the human body exergy model developed by Shukuya et al is elaborated in the second section. Simone et al. tested the model on the relation between human-body exergy consumption rates and thermal sensation, based on data from earlier thermal comfort studies. They showed that the minimum human body exergy consumption rate is associated with thermal sensation votes close to thermal neutrality, slightly tending towards the cool side of thermal sensation. Both convective and radiant heat exchange between the subject and the enclosure were considered to result in minimum human body exergy consumption rates at relative humidity (RH) lower than 50% and operative temperature (t_o) within 22 °C and 24 °C. For higher RH (circa 85%), the human-body exergy consumption rates decrease when t_o is increasing above 24 °C. The results indicated that there is a high influence of radiant heat and relative humidity on the Human Body exergy consumption rate. The thermal sensation vote is based on a subjective evaluation of the thermal environment and it therefore takes into account the influence of all possible heat transfer mechanisms and relevant personal parameters (clothing, activity level, etc.). Operative temperature should be used as an explaining variable when exploring human body exergy consumption, as it accounts for both convective and radiant heat transfer between the human body and the surrounding environment.

The third section of this chapter presents a study by Dovjak et al. considering the influence of relative humidity, indoor microclimate conditions and individual parameters on separate components of human body exergy balance and predicted mean vote (PMV). The results show the effect of relative humidity and air temperature on thermal comfort conditions and human body exergy rate, especially in extreme conditions. Hot and dry or cold and dry environments resulted in the largest human body exergy consumption rate and the minimum rate was found in a hot and humid environment.

These results are also confirmed by Dovjak et al. in the fourth section, based on field studies in a building with low exergy systems (LowEx) located in Ljubljana. Periodical monitoring of two test-rooms, one with LowEx and the other with conventional heating/cooling systems, showed that human body exergy rates and PMV index vary among individuals for both systems. Better thermal comfort conditions were created in the room with the LowEx system, where surface temperatures were higher than air temperatures and PMV was closer to neutral (PMV=0). Besides, circa 50% of reduction of energy use for cooling and heating was measured when the LowEx system was used.

The use of different concepts of high-mass heating/cooling systems (reducing energy consumption, as in naturally ventilated buildings) is associated with indoor temperature drifts. Detailed evaluations and analyses are presented in the last three sections of this chapter.

In the fifth section, Kolaric et al. report on their climate chamber studies, where they looked at occupants' thermal comfort, perceived air quality, perception of sick building syndrome (SBS) symptoms and office work performance. The authors reviewed the basis for evaluation of drifting temperatures' impact on building occupants, and concluded that occupants' responses to temperature drifts can be based on steady-state evaluations when drifts are lower than 4K per hour as in most buildings.

Toftum et al. analysed the clothing adjustment opportunity, reproducing the structures and criteria of the previous work. In the sixth section they present their results, which showed that longer exposures to increasing temperatures may increase the intensity of general SBS symptoms when no opportunity to adjust clothing insulation is available.

In the last section, Schellen et al. describe the effect of ageing on thermal comfort and productivity, focusing on the effect of a moderate temperature drift on physiological responses, thermal comfort and productivity of young adults (age 22-25yr) and older subjects (age 67-73yr). The results indicate that thermal sensation of the elderly is, in general, 0.5 scale units lower in comparison to their younger counterparts so that they prefer a higher temperature.

5.1 Recent Development of Human Body- Body Exergy Balance Model and Thermal Comfort in Buildings

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5.1.1 Introduction

Research on the built environment from an exergetic viewpoint has grown since the early 1990's (Shukuya and Hammache, 2002). In due course, the exergy concept was developed and sharpened in order to make it applicable to the field of building physics and its related areas such as indoor thermal environmental science. Exergy analysis of the built environment equipped with space heating and cooling systems shows how much and where exergy is consumed in the whole process from its supply and consumption to the resultant entropy generation and disposal (Shukuya and Hammache, 2002; Shukuya, 2004). Space heating and cooling systems are physical systems; their purpose is to control the built environmental condition within a certain range that allows the occupants to be healthy and comfortable with rational ways of exergy consumption (Shukuya, 2007).

Physics, with respect to the built environment and its technology, must be in harmony with human physiology and psychology. In this sense, it is of vital importance to have a better understanding of the human-body as a thermodynamic system at dynamic state from the exergetic viewpoint. This section briefly introduces a state-of-the-art development of human-body exergy balance and describes some results of its numerical analysis assuming typical indoor and outdoor environmental conditions in winter and in summer.

5.1.2 Setting up an exergy balance equation

Generally speaking, a thermodynamic system to be investigated is regarded to reside surrounded by its environmental space. The whole of the system and the environment is regarded to be the universe. Any working system works, feeding on some energy and matter, while at the same time, storing portions and/or giving off remainders. In due course, the whole amount of energy is conserved while on the other hand, an amount of entropy is generated. The generated entropy may be stored for a while, but sooner or later it must be discarded into the environment.

A portion of energy, whose associated temperature, pressure and chemical potential are in equilibrium with their corresponding values in the environment, has no capability of dispersion. Another portion of energy, which has not yet dispersed, has a capability of dispersion and corresponds to the exergy which is the driving agent for the system. As can be seen in the left side of Figure 1, a working system feeds on exergy from a source and dumps the generated entropy, which is proportional to the exergy consumption within the system, into the environment. We call such a process an “Exergy- Entropy process” (Shukuya and Hammache, 2002; Shukuya, 2004).

The exergy balance equation for the system can be set up in a general form as:

[Exergy input] – [Exergy consumed] = [Exergy stored] + [Exergy output] (1)

In order to set up the detailed form of equation (1), an energy balance equation was set up according to “the law of energy conservation (the 1st law)” and then the corresponding entropy balance equation according to “the law of entropy generation (the 2nd law)”. Extraction of the product of the entropy balance equation and the environmental temperature from the energy balance equation brings about the *exergy* balance equation. The whole procedure is shown on the right side of Figure 1.

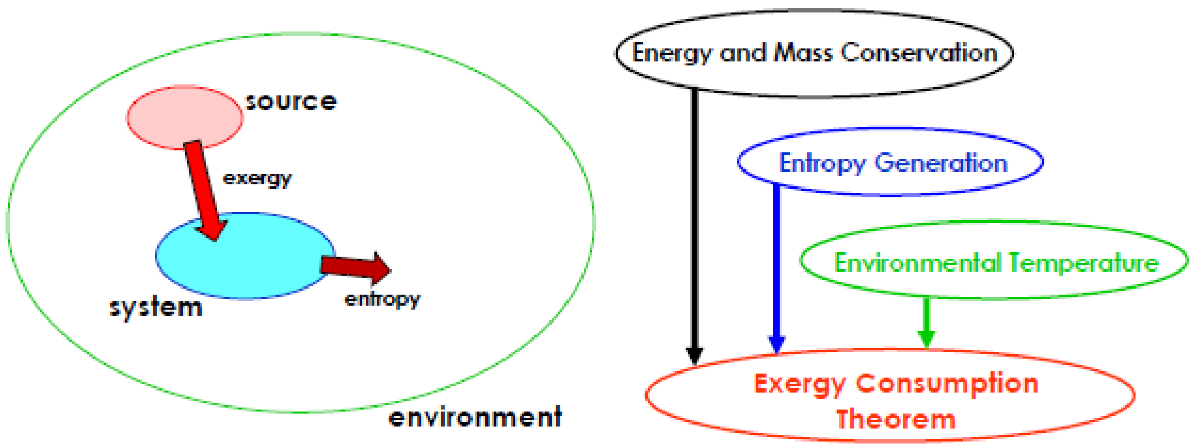

Figure 1: A system and its environment. The system performs an “exergy-entropy” process. The exergy balance equation is derived from energy and entropy together with the environmental temperature.

5.1.3 The human-body exergy balance equation

The thermal exergy balance equation of a human body as a two-node model of core and shell is derived by combining the energy and entropy balance equations together with the environmental temperature for exergy calculation, which is the outdoor air temperature (Shukuya, 2004; 2009).

The exergy balance for the whole of core and shell of the body is considered. The exergy balance for the whole of the human body is build up of an exergy stream from the core to the shell and several exergy streams from the surrounding space, eventually via clothing, to the skin minus exergy consumption is equal to the exergy streams from the skin, eventually via clothing, (mainly to the environment) plus the accumulation of exergy in the shell and core (in a steady state this last term is zero).[1]

If an overall investigation of the human-body exergy balance is made together with the building heating/cooling system's exergy balance, the environmental temperature must be the same for both the human body and the heating/cooling system.

The first term of equation (2) is the warm exergy output of the core as the result of chemical exergy conversion for a variety of cellular activities. The main activities are contraction of muscles, composition of proteins and sustenance of the relative concentrations of various minerals in the body cells.

The exergy-consumption in the last term of the left side of equation (2) is due to the result of two kinds of dispersion. The first one is thermal dispersion caused by the temperature difference between the body core, whose temperature is almost constant at 37 ºC, and the body shell, namely the skin, whose temperature ranges from 30 to 35 ºC, and the clothing surface, whose temperature ranges from 20 to 35 ºC. The second one is dispersion of liquid water into water vapour, in other words, free expansion of water molecules into their surrounding space.

[Warm exergy generated by metabolism]
+ [Warm/cool and wet/dry exergies of the inhaled humid air]
+ [Warm and wet exergies of the liquid water generated in the core by metabolism]
+ [Warm/cool and wet/dry exergies of the sum of liquid water generated in the shell by metabolism and dry air to let the liquid water disperse]
+ [Warm/cool radiant exergy absorbed by the whole of skin and clothing surfaces]
- [Exergy consumption]
= [Warm exergy stored in the core and the shell]
+ [Warm and wet exergies of the exhaled humid air]
+ [Warm/cool exergy of the water vapor originating from the sweat and wet/dry exergy of the humid air containing the evaporated water from the sweat]
+ [Warm/cool radiant exergy discharged from the whole of skin and clothing surfaces]
+ [Warm/cool exergy transferred by convection from the whole of skin and clothing surfaces into the surrounding air]. (2)

[1] The complex process of food intake and excretion is simplified in one term "warm exergy generated by metabolism". [addition of the editor].

All terms in the right side of equation (2) - except the first term, exergy storage - play important roles in disposing of the generated entropy due to chemical and thermal exergy consumption within the human body. These processes of outgoing exergy flow together with exergy consumption have a large influence on human well-being in terms of health and comfort.

5.1.4 Some numerical examples and discussion thereof

Two examples of the whole exergy balance of a human body in a winter condition of outdoor air temperature and relative humidity of 0 ºC and 40% are shown in Figure 2 (Shukuya, 2009). The twin-bar graphs to be discussed here are consistent with the expression given in equation (2), once the term of *exergy consumed* is moved to the right side of the equation. The indoor operative temperature was assumed to be 22 ºC in both examples. The combination of mean radiant temperature and surrounding air temperature were not the same: they were 19 ºC and 25 ºC, and 25 ºC and 19 ºC.

Although the exergy input consists of five components as shown in equation (2), the three components associated with the inhaled humid air and liquid water, emerged in the core and in the shell, were much smaller than the other two components in winter conditions. Therefore they were included in the portion of “Humid air + Water”. Since the exergy stored was also very small compared to the exergy consumption, it was not apparent in the bars shown in Figure 2. The exergy-consumption rate amounts to 20 - 30 % of the input exergy rate and differs per case. The exergy consumption was lower in the case where the mean radiant temperature was higher than the room air temperature, for winter conditions. The sum of relative rates of warm radiant exergy emission and convective warm exergy transfer was very large in the case of the mean radiant temperature higher than the surrounding air temperature. This was due to the higher mean radiant temperature resulting in a higher average temperature of the skin and clothing surfaces which leads to a smaller exergy consumption rate. Such a condition must relate to providing the human body with a higher level of thermal comfort.

Figure 3 shows two other examples of the whole human-body exergy balance in typical summer conditions: hot and humid, outdoor air temperature and relative humidity of 33 ºC and 60%, respectively (Shukuya, 2009). The twin-bar graph at the top shows a case of radiant cooling together with natural ventilation and that at the bottom a case of mechanical air cooling. For the former, the surrounding air temperature, humidity and air velocity were assumed to be 30 ºC; 65% and 0.3 m/s, respectively, and for the latter, 26 ºC; 50 %, and 0.1 m/s, respectively. For both cases, the mean radiant temperature was assumed to be 27 ºC.

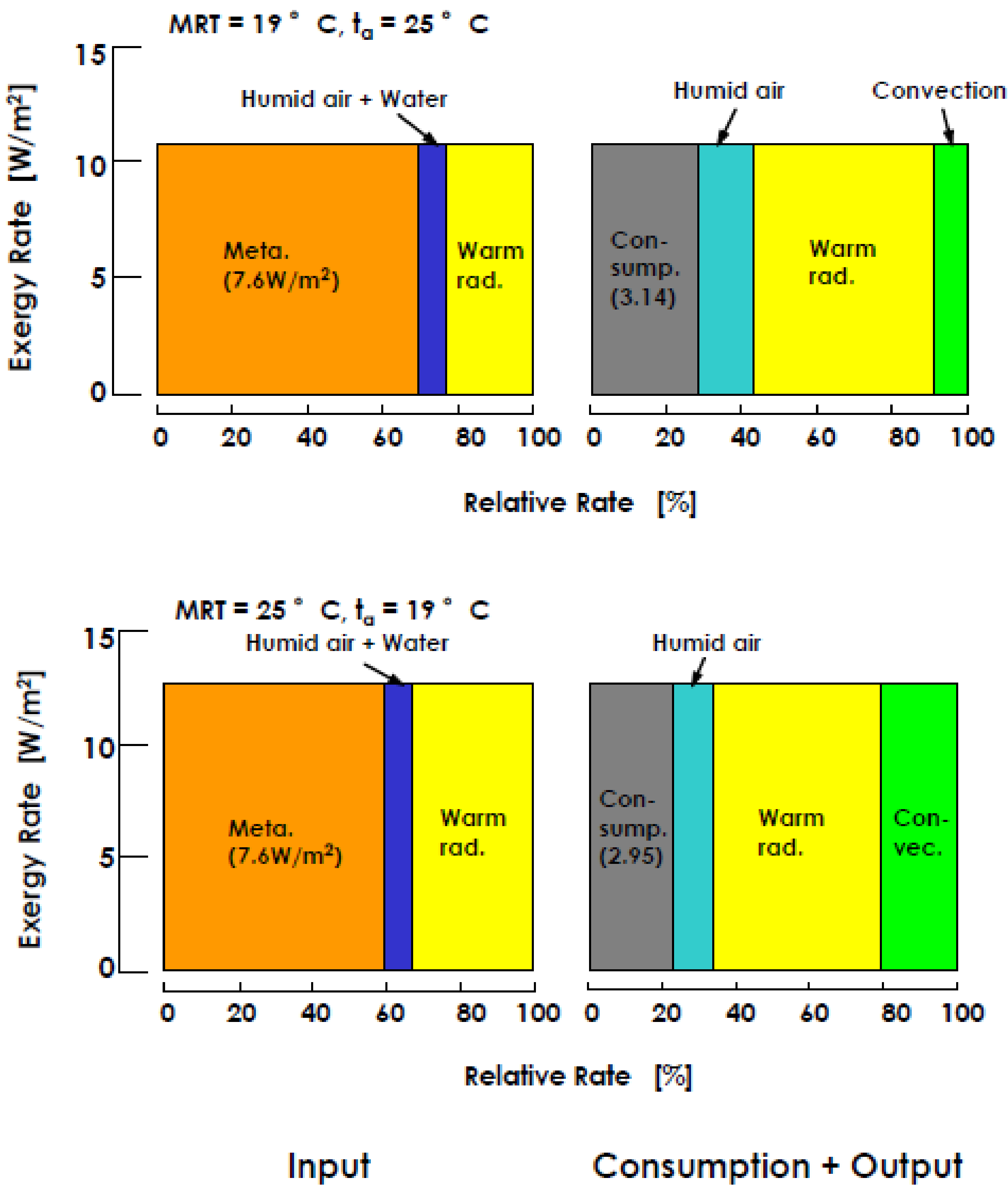

Figure 2: Two examples of the whole human-body exergy balance in typical winter conditions: outdoor air temperature and relative humidity of 0 °C and 40%, respectively. Exergy stored is negligibly small and therefore not shown.

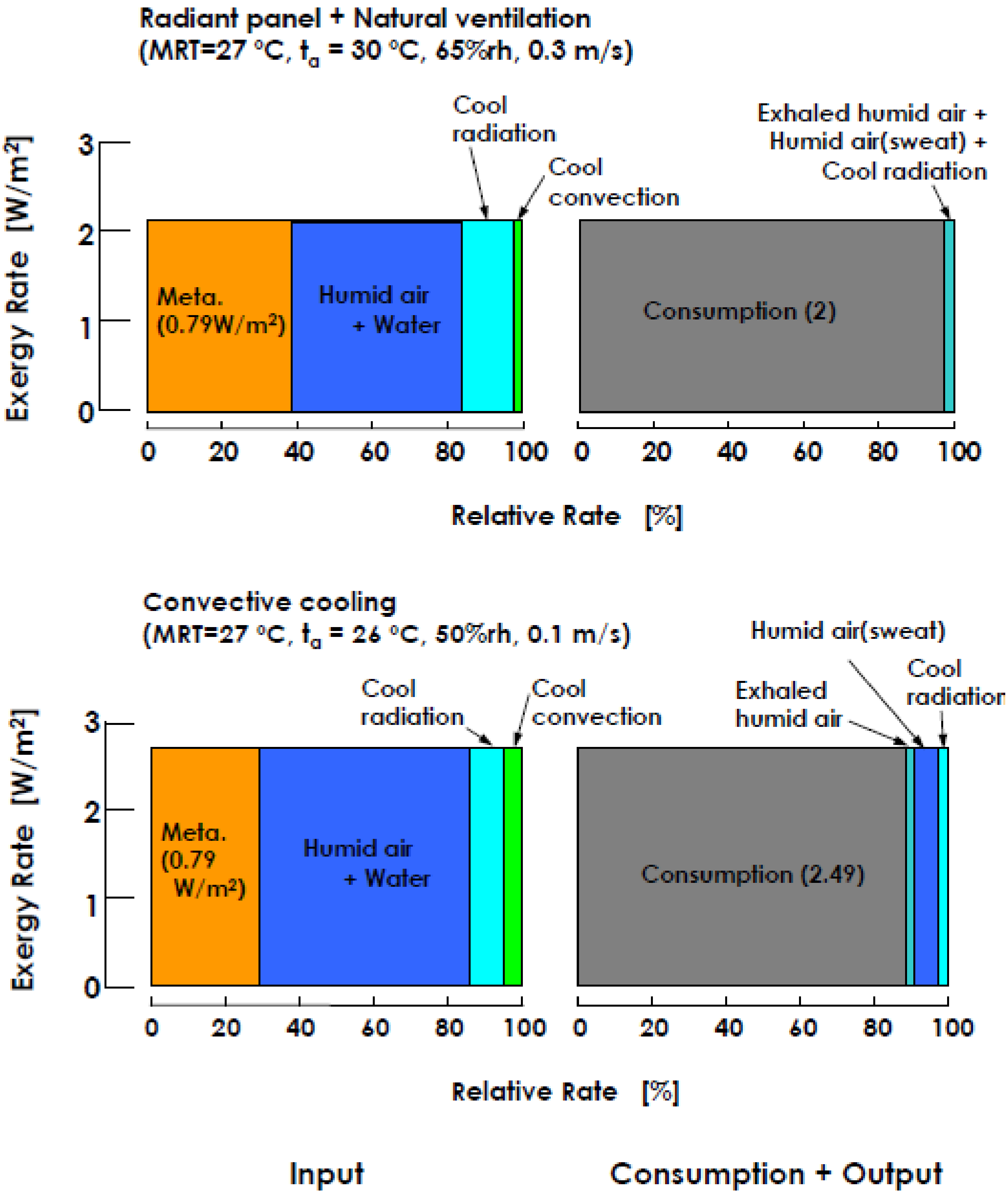

Figure 3: Two examples of the whole human-body exergy balance; typical summer conditions: outdoor air temperature and relative humidity of 33 ºC and 60%, respectively. Exergy stored and exergy contained by the inhaled air is negligibly small and therefore not shown.

The profiles of the exergy balance in summer cases were quite different from those in winter cases. There are four apparent differences. One is that the absolute values of exergy input rate in summer are much smaller than those in winter. This is because of the small temperature difference between in- and outdoors in summer. The second is that the relative rates of wet exergy contained by liquid water, especially in the body-shell, are much larger than those in winter due to more sweat secretion in the case of radiant cooling and also due to dryness of room air in the case of convective cooling. The third is that there is cool exergy given by convection in addition to radiation, though its relative magnitude is smaller than that of cool radiant exergy. The fourth is that the relative rates of exergy consumption are very large compared to the output exergy rates.

The wet exergy of liquid water inside the human body and the cool radiant exergy coming onto the human body in addition to cool exergy transferred by convection let the metabolic “warm” exergy be consumed in order to maintain the human body within a thermally desirable state. The relative magnitude of the output exergy rates was very small in comparison to exergy consumption, but this does not imply that it is less important; they are essential in disposing of the generated entropy inside the human body due to exergy consumption of “warm” and “wet”/”cool” exergies. In other words, the output exergy rates were small, since they contained a lot of entropy to be discarded into the environmental space.

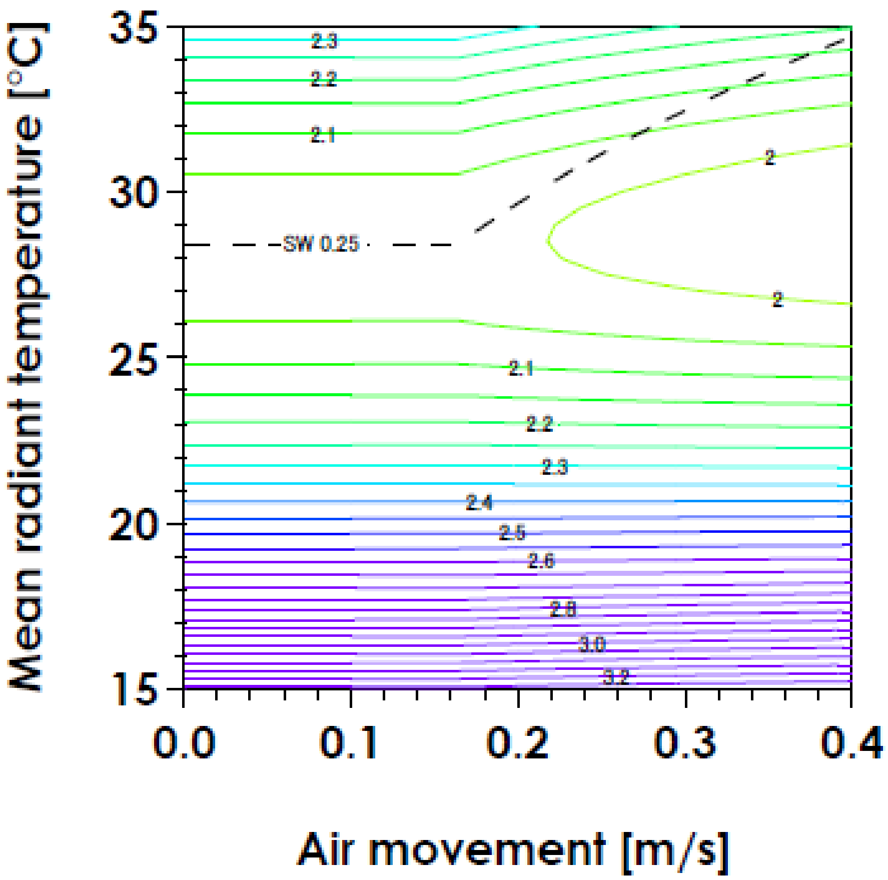

Figure 4: Relationships between human-body exergy consumption rate, whose unit is W/m^2 (body surface), and the combination of mean radiant temperature and air movement (air velocity) under a summer condition (33ºC; 60%RH). Room air temperature and relative humidity are assumed to be ***30 ºC; 65%RH*** *for the indoor air condition by natural ventilation.*

A series of recent studies (Iwamatsu et al, 2008; Shukuya, 2009) shows that there seems to be a set of mean radiant temperature and air velocity combinations giving the lowest human-body exergy consumption rate. Figure 4 shows the relationship between the human-body exergy consumption rate, whose unit is W/m^2 (body surface), and combinations of mean radiant temperatures and air velocities under a summer condition (33ºC; 60%RH) in the case of radiant cooling combined with natural ventilation. Here it was assumed that room air temperature and relative humidity were 30 ºC and 65 %, respectively. Such a room air condition during daytime at outdoor air temperature and relative humidity of 33 ºC and 60% can be realized by natural ventilation together with radiant cooling wall or ceiling panels, a thermally-activated building-envelope system, or with the cool storage by floor, walls and ceiling due to nocturnal ventilation by either an active system or a passive system realized during the previous days (Shukuya, 2007).

A combination of mean radiant temperatures controlled lower than 30 ºC, for example in the range of 28 to 29 ºC, and air velocities exceeding 0.2 m/s provides the human body with his/her lowest exergy consumption rate, slightly lower than 2 W/m^2. The lowest exergy-consumption rate turns out to be about 2 W/m^2 for the air velocity smaller than 0.2 m/s. In a naturally ventilated room space, almost random natural fluctuation of soft air movement (breeze) brings about pleasant coolness, which is called “*Suzushisa*” in Japanese. This is a rather dynamic condition different from static neutrality of neither hot nor cold. A dashed line represents the condition at skin-wettedness of 0.25, over which the human body is not tolerant. It is interesting that the lowest values of exergy-consumption rate lie just below this line.

The human-body lowest exergy consumption rate can also be given in the case of convective cooling as shown in Figure 5. In this example, room air temperature and relative humidity were assumed to be 26 ºC; 50%. The lowest exergy-consumption rate of 2.3 W/m^2 or less are in the range of 0.3 to 0.4 m/s of air movement with a mean radiant temperature of about 26ºC, although such a high air velocity around the human body in a mechanically air-conditioned space can result in discomfort. Therefore, the air current for mechanical cooling mainly by the use of convection should be reduced to the air velocity of 0.15 m/s at the highest.

If the air velocity was 0.1 m/s, the lowest exergy consumption rate of around 2.4 W/m^2 was found with the mean radiant temperature of 24 ºC, which is 2 ºC lower than the room air temperature assumed for this calculation. There are usually some radiant heat sources such as glass windows absorbing more or less the incident solar radiation and electric-lighting fixtures mounted on the ceiling, computer screens and so on. Therefore, the mean radiant temperature was usually much higher than 24 ºC, namely 29 ºC to 30 ºC. There were some cases where it reached even higher, almost 31 ºC. If this was the case, the human-body exergy consumption rate became slightly larger, from 2.5 to 2.7 W/m^2.

The discussion above suggested that passive strategies for indoor thermal environment control such as solar control by an external shading device over glass windows and natural ventilation should come to the first priority. Only after passive measures are in place one should resort to the use of suitable active cooling systems, i.e. radiant cooling, (Shukuya, 2008). The development of low-exergy cooling systems is to be made on this direction, which is consistent with that of low-exergy heating systems.

According to the previous studies with respect to human-body exergy balance, there is a thermal environmental condition which brings about the lowest exergy consumption rate (Isawa et al., 2002, 2003; Prek, 2005). It resulted interestingly that there is such a condition that brings about the lowest exergy consumption rate even in summer.

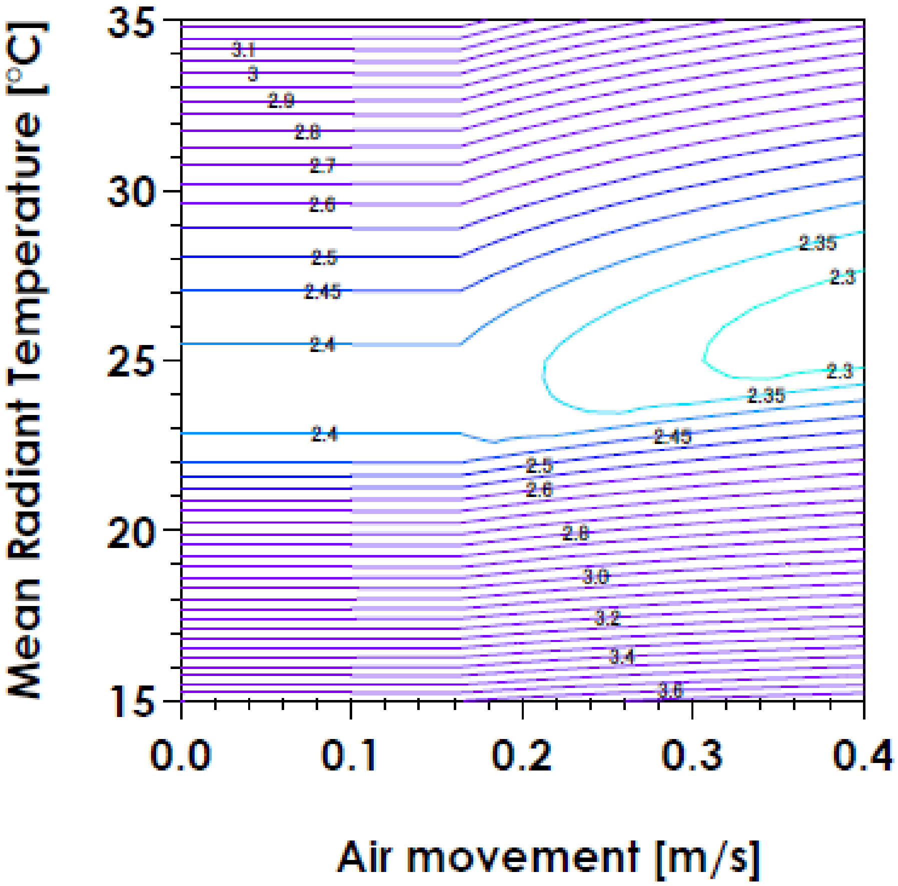

Figure 5: Relationships between human-body exergy consumption rate, whose unit is W/m^2 (body surface), and combinations of mean radiant temperatures and air movements under a summer condition (33ºC; 60%RH). Room air temperature and relative humidity are assumed to be ***26 ºC; 50%RH*** *for the indoor air condition by convective cooling.*

5.1.5 Conclusion

A state-of-the-art development of the human-body exergy balance equation is described briefly and some numerical results were discussed. “Warm” radiant exergy played an important role in winter conditions, while on the other hand in summer conditions it was essentially “wet” exergy in addition to the reduction of warm exergy and the enhancement of cool radiant exergy. A lowest exergy-consumption rate of the human-body for summer conditions such as a lowest rate for winter conditions suggested that the control of long-wavelength radiation is very important in summer to make an effective use of natural ventilation.

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5.2 Human body exergy consumption rate and assessed thermal sensation: air and mean radiant temperatures influence

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5.2.1 Introduction

The applicability of the exergy concept in the case of energy-flow analysis in buildings and communities has been demonstrated in several studies (Shukuya and Hammache, 2002; IEA, 2003; IEA, 2005; Schmidt, 2004; Schmidt, 2009; Sakulpipatsin, 2008; CostAction24-CostExergy, 2009). These studies show that most of the energy used in buildings is to maintain a satisfactory indoor environment for the occupants (e.g. control of room temperature, relative humidity, lighting and hot water preparation). In particular, in heating and cooling applications, the amount of exergy needed to maintain acceptable indoor temperatures, which are usually recommended within the range from 20 °C to 26 °C, is generally low.

To provide a healthy and comfortable environment for its occupants, the exergy flow in buildings and those within the human body should be considered.

A relationship between the human-body exergy consumption rate, room air temperature and mean radiant temperature was first explored by Isawa et al. (2003) and by Shukuya et al. (2010). They compared values of human-body exergy consumption rate for different combinations of air and mean radiant temperature to the Predicted Mean Votes (PMV), which predicts the average thermal sensation of a large group of people. Isawa and Shukuya concluded that the lowest exergy consumption occurred at a certain point on the line representing thermal neutrality (PMV=0), especially under winter conditions (0 °C, 40% RH). Those studies and a study by Prek (2004) calculated human-body exergy consumption rate and compared it to results obtained from the PMV model.

By ensuring that climate conditioning systems provide thermal comfort with the lowest possible human-body exergy consumption rate, the exergy concept makes it possible to combine environmental characteristics, indoor environment parameters and human physiological responses in such a way that both thermal comfort and energy savings can be achieved.

There is a need to verify the human-body exergy model with the Thermal-Sensation (TS) response of subjects exposed to different combinations of indoor climate parameters (temperature, humidity, etc.). By using the human-body exergy model, Simone et al. (2011) investigated the relationship between the human body exergy consumption rate and the thermal sensation response of subjects exposed to different combinations of convective and radiant heat exchange. First results showed that the minimum human body exergy consumption rate is associated with subjectively assessed thermal sensation votes (TSV) close to thermal neutrality, tending to the slightly cool side of thermal sensation. Later, additional data assessing indoor thermal comfort for Thai people (2010) were included in the evaluation of low human-body exergy consumption rate.

Taking account of both convective and radiant heat exchange between the human body and the surrounding environment with an operative temperature (t_o), the exergy consumption rates increase as t_o increases above 24°C or decreases below 22°C when the relative humidity (RH) is lower than 50%. While, when RH is high (80%-90%), the human body exergy consumption rates have a tendency to decrease when t_o is increasing above 24 °C.

5.2.2 Methodologies

Analysed data and experimental conditions

Data available from several previous subjective experiments, concerning thermal comfort studies, were collected and human-body exergy consumption rates were quantified. The analyses take into consideration available data from studies regarding the relative effects of convective and radiant heat transfer on thermal sensation of sedentary subjects at constant values of relative humidity. In addition, the available data was collected from experiments conducted in a climate chamber, which allowed controlling the indoor climate parameters.

McNall and Schlegel (1968) and Simone and Olesen (2009) investigated the relative effects of convection and radiation on thermal comfort by statistically analysing the thermal sensation responses of many subjects (respectively, 20 and 30, both male and female) to different combinations of mean radiant temperature and air temperature. All other variables affecting thermal sensations were kept constant, respectively: RH=45% and 50%, air velocity= 0.14 m/s and 0.05 m/s, activity level= 1met and 1.1 met. The investigation was conducted for conditions within the zone of thermal neutrality.

McNall and Biddison (1970) studied the thermal sensation of 160 subjects (85 male and 85 female) exposed to asymmetric radiant fields. The subjects were exposed to four separate types of experimental series: cool wall series, hot wall series, hot ceiling series and control. The metabolic rate was estimated to be approximately 1.2 met, while the mean air velocity was 0.10-0.15 m/s and RH equal to 45%.

McIntyre and Griffiths (1972) studied subjective responses to combinations of radiant and convective environments. All together 16 male subjects were exposed to different combinations of air (in the range 15-36°C) and mean radiant (17-32°C) temperatures. Mean air velocity was 0.07 m/s and the relative humidity ranged from 16 % to 54%.

Taweekun and Tantiwichien (2010) investigated thermal comfort assessments in an environment where radiant cooling panels were used. Subjective experiments were carried out to evaluate thermal comfort under the radiant cooling system of Thai people. The radiant cooling panels were installed at the wall and the ceiling of the experimental room. The human subjects expressed their thermal sensation by using the seven-point Thermal Sensation Scale. Experimental conditions for humidity and air movement were controlled by a humidifier and air speed level. The available data used for the analysis and the calculation of the human body exergy consumption rate are reported in Table 1.

Condition	**Activity level [met]**	**Air velocity [m/s]**	**RH [%]**	**I_{cl} [clo]**	**t_a [°C]**	**TSV [-]**
1	1.1	0.2	80-90	0.5	24	-0.4
2	1.1	0.2	80-90	0.5	25	-0.2
3	1.1	0.2	80-90	0.5	26	-0.1
4	1.1	0.2	80-90	0.5	27	0.2
5	1.1	0.2	80-90	0.5	28	0.2
6	1.1	0.2	80-90	0.5	29	0.1
7	1.1	0.2	80-90	0.5	30	0.9
8	1.1	0.2	80-90	0.5	32	1.1
9	1.1	1	80-90	0.5	24	-2.0
10	1.1	1	80-90	0.5	25	-1.6
11	1.1	1	80-90	0.5	26	-0.9
12	1.1	1	80-90	0.5	27	-0.9
13	1.1	1	80-90	0.5	28	-1.0
14	1.1	1	80-90	0.5	29	-0.5
15	1.1	1	80-90	0.5	30	-0.5
16	1.1	1	80-90	0.5	31	-0.2
17	1.1	1	80-90	0.5	32	-0.4

Table 1: Data collected from the study of Taweekun and Tantiwichien (2010)

Calculation of the human-body exergy consumption

The human-body exergy consumption rate is determined so that the human-body exergy balance equation is satisfied. The exergy balance equation for the system can be set up in a general form as:

$$[\text{exergy input}] - [\text{exergy consumed}] = [\text{exergy stored}] + [\text{exergy output}] \qquad (1)$$

The thermal exergy balance of the human body, consisting of two subsystems (core and shell), is shown in simplified form in equation (2) by combining the energy and entropy balance equations together with the environmental temperature to express the exergy balance used for calculations (Shukuya et al., 2010).

$$(Ex_{W,met} + Ex_{inhaled} + Ex_{water,core} + Ex_{water,shell} + Ex_{R,absorbed}) - Ex_{cons} =$$

$$(Ex_{warm-stored} + Ex_{exhaled} + Ex_{sweat} + Ex_{R,released} + Ex_{C}) \qquad (2)$$

Where the terms, occurring in equation (2), are the same as explained in item 5.1.3. of this book:

<table>
<tr><td colspan="2">[Warm exergy generated by metabolism]
[Warm/cool and wet/dry exergies of inhaled humid air]
[Warm and wet exergies of liquid water generated in the core by metabolism]
[Warm/cool and wet/dry exergies of the sum of liquid water generated in the shell by metabolism and dry air to let the liquid water disperse]
[Warm/cool radiant exergy absorbed by the whole of skin and clothing surfaces]</td><td>–</td><td>[Exergy consumption]</td></tr>
<tr><td>=</td><td colspan="3">[Warm exergy stored in the core and the shell]
[Warm and wet exergies of exhaled humid air]
[Warm/cool radiant exergy discharged from the whole of skin and clothing surfaces]
[Warm/cool exergy of water vapour originating from the sweat and wet/dry exergy of the humid air containing the evaporated water from the sweat]
[Warm/cool exergy transferred by convection from the whole of skin and clothing surfaces into the surrounding air]</td></tr>
</table>

Environmental temperature

Among a variety of thermodynamic concepts such as energy, entropy or free energy, the exergy concept is unique since it relates not only internal parameters of a system, such as indoor temperature, but also the parameters of the outdoor environment surrounding the system in question (Saito et al., 2000).

Lack of knowledge about the outdoor environmental physical parameters made the authors assume outdoor environmental temperature and relative humidity to be equal to the indoor air temperature and relative humidity.

5.2.3 Results

The human body exergy consumption rates reported in table 2 were calculated for the value ranges reported in table 1 and in the earlier mentioned studies found in literature. Additionally results of human body exergy consumption calculated for the values representative of a thermally comfortable environment (when thermal sensation is ±0.5) were inserted.

Those results are represented in figure 1 where the relationship between human body exergy consumption rate and the subjectively thermal sensation votes (TSV) is shown.

	Ex (T_a, RH) [W/m^2]	
Analysed study	**all data**	**when TSV=±0.5**
McNall and Schlegel (1968)	2.3÷3.0	2.4
McNall and Biddison (1970)	3.1÷3.5	3.1÷3.5
McIntyre and Griffiths (1972)	2.7÷4.7	2.7÷3.4
Simone and Olesen (2009)	2.5÷2.6	2.5÷2.6
Taweekun and Tantiwichien (2010)	1.3÷2.2	1.3÷2.0

Table 2: range of human body exergy consumption rate calculated from literature studies.

The increasing trend of exergy consumption rate is consistent with the thermal sensation votes increasing above *neutral* for most of the analysed thermal conditions. On the other hand, below *neutral* thermal sensation the data-points are rather scattered. Nevertheless, most of the data support the assumption that in the range of thermal sensations close to the thermal neutrality the minimum human body exergy consumption rate can be expected.

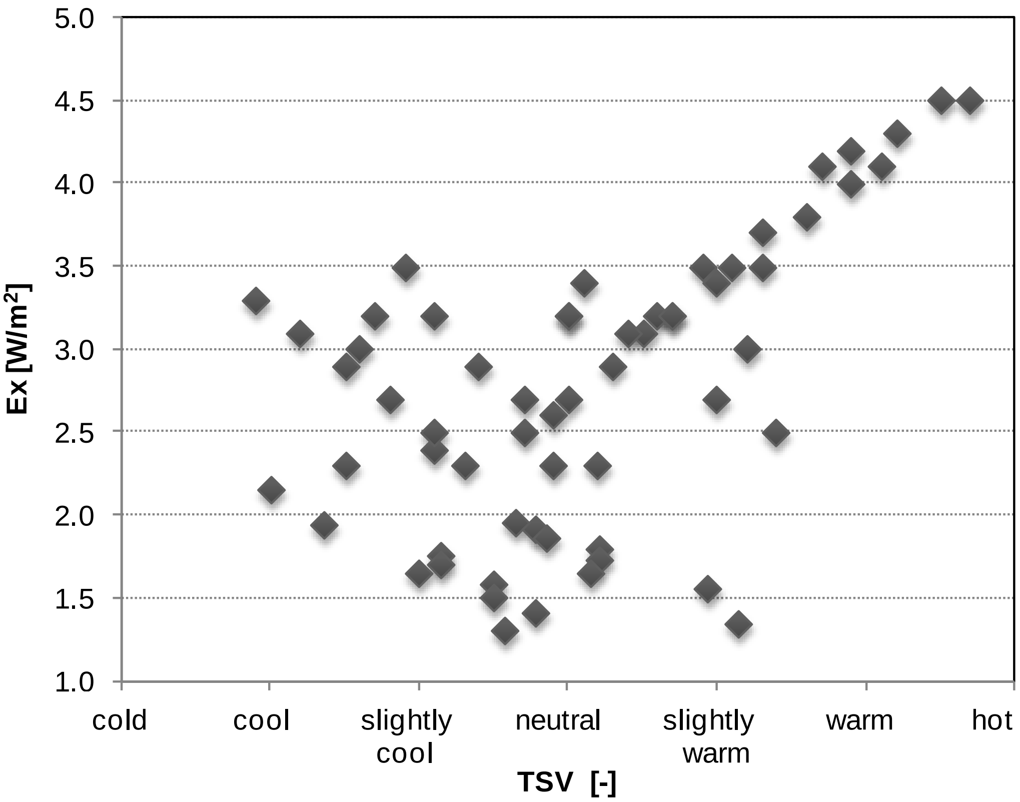

Figure 1: Data used for the analysis and calculation of the human body exergy consumption rate.

Often a first-hand crude estimation of the human thermal comfort refers only to the air temperature measurement. For that reason, the relationship between the calculated exergy consumption rate and air temperature is evaluated and depicted in figure 2.

There seems to be an increasing trend for data from McIntyre and Griffiths – as the air temperature increases so does the exergy consumption rate, while the opposite is visible for the data collected during experiments for the conditions reported by Taweekun and Tantiwichien (2010). Data from a study by McNall and Schegel (1968) appear to be almost unrelated to air temperature.

However, when the convective and the radiant heat exchange are considered, the relationships between the exergy consumption rate and the operative temperature (see figure 3) are more concentrated in a zone. In particular, the exergy consumption rate increases not only as the operative temperature increases (from about 24°C), but also when it decreases below approx. 22°C. In figure 3 the data of Taweekun and Tantiwichien's (2010) study are omitted as the measured values of operative temperatures were not reported in the published work.

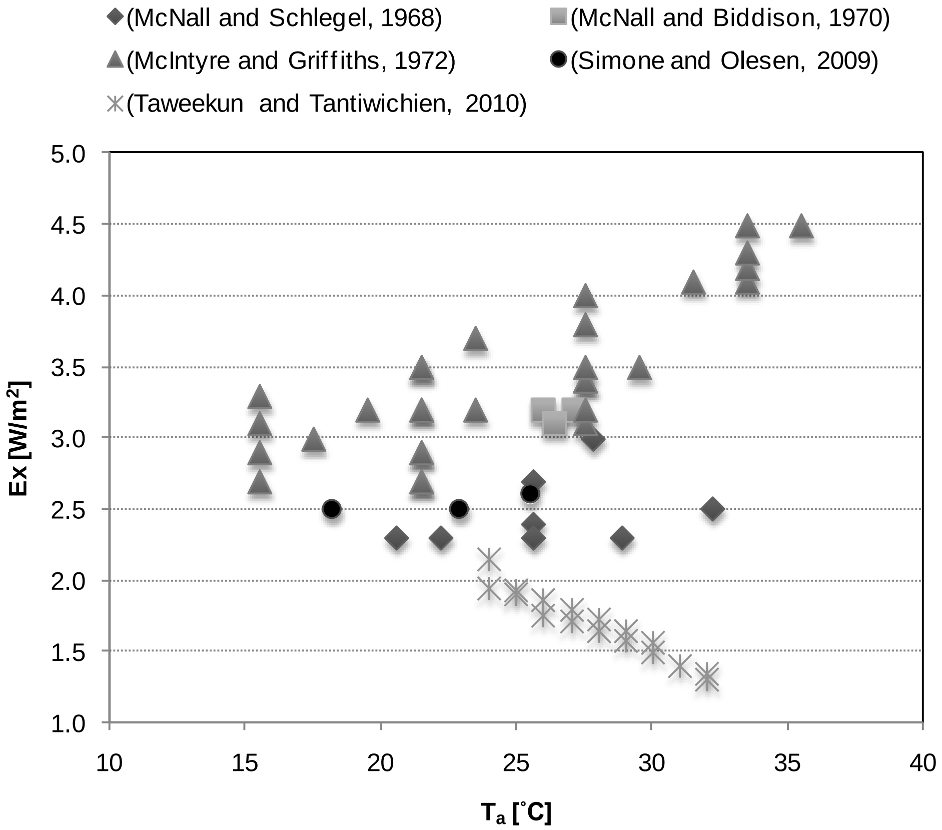

Figure 2: Human body exergy consumption rate as a function of air temperature

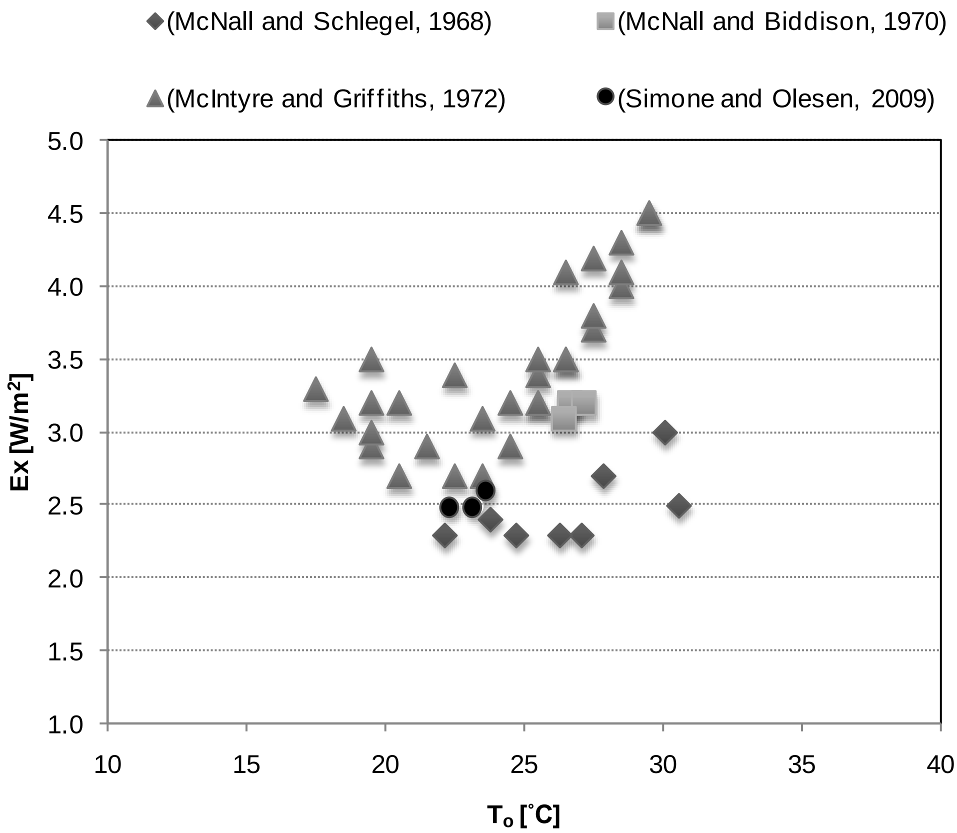

Figure 3: Human body exergy consumption rate as a function of operative temperature.

A real indoor environment, controlled by a heating, ventilation and air conditioning (HVAC) system, can be designed to provide the best indoor thermal conditions for the occupants at the lowest exergy consumption. The HVAC system can control thermal parameters such as air and mean radiant temperature, in such a way that a minimum human body exergy consumption rate is required for a thermally neutral sensation when the predicted mean vote is neutral (PMV=0)).

For summer and winter seasons, the temperature set points for the heating and cooling system might be defined so as to yield 23°C operative temperature , as suggested in many thermal comfort standards. In this case, which values of air temperature and mean radiant temperature are permissible?

Naturally, equal or different values of air temperature and mean radiant temperature can be easily obtained. Hypothesizing that the difference between air and mean radiant temperature should be 6K, the exergy consumption rate is then calculated.

Figure 4 shows some results of the exergy consumption rate plotted as a function of both air and mean radiant temperature, assuming that the outside air temperature is equal to mean air temperature indoors. The diamond-shaped dots in figure 4 show that the exergy consumption rate, for PMV=0, was higher when the mean radiant temperature was lower than the mean air temperature (2.7W/m^2 against 2.5W/m^2).

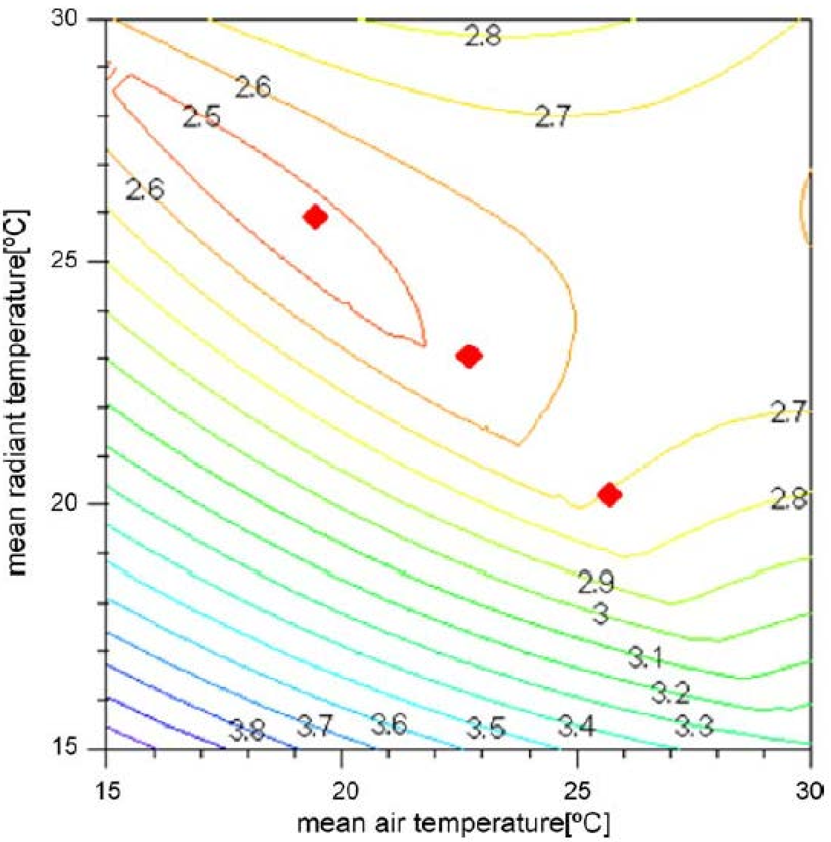

Figure 4: Human body exergy consumption rate (W/m^2) when HVAC systems are applied for PMV=0.

5.2.4 Discussion

Figures 2 and 3 show a different distribution of the analysed values as a function of the calculated exergy consumption rate of the human body. The difference is mainly associated with the omission of the effect of radiant heat exchange, which is relevant for defining indoor thermal comfort conditions. The results showed that the radiant heat parameter is very important for evaluating the exergy consumption rate, and that mistakes may occur when looking only at the room air temperature (and not at both air and mean radiant temperature). The difference highlights the fact that air temperature alone cannot be an explaining variable for the human body exergy consumption rate as it represents only a part of the heat transport mechanism important for the human body.

However, the relationship depicted in Figure 3 seems to be in agreement with previous research (Saito et al., 2000) considering the environmental temperature equal to indoor air temperature, in which the human body exergy consumption rate had its minimum at the operative temperature range 22-24°C.

The utilization of operative temperature as an explaining variable when exploring human body exergy consumption has obvious practical advantages, as it is a well-adapted index to describe human thermal environment and is widely used in many thermal comfort standards.

The thermal sensation vote is based on a subjective evaluation of the thermal environment and it therefore takes into account the influence of all possible heat transfer mechanisms and relevant personal parameters (clothing, activity level, etc.). It is clear from Figure 1 that the minimum exergy consumption rate occurred close to subjective thermal neutrality, more precisely within the “slightly cool-neutral” interval. This kind of relationship was previously determined by Isawa et al. (2003) and Shukuya (2006) by comparison of the exergy consumption rates and the values of the PMV index calculated for corresponding conditions.

Usually, air velocity and relative humidity are fixed. An exception is McIntyre and Griffith’s work that analysed more experimental conditions with different combinations of air temperature, mean radiant temperature and relative humidity.

Figure 5, where the results of human-body exergy consumption rates for the different analysed studies are represented, shows that the lowest values are closer to neutral thermal sensation (0) tending to the slightly cool (-1). At the same time, it shows the different tendency of the exergy consumption values in warmer or cooler zones from different studies. In particular, it is noticeable that there is a decrease in the human-body exergy consumption rate with an increase in relative humidity and air velocity.

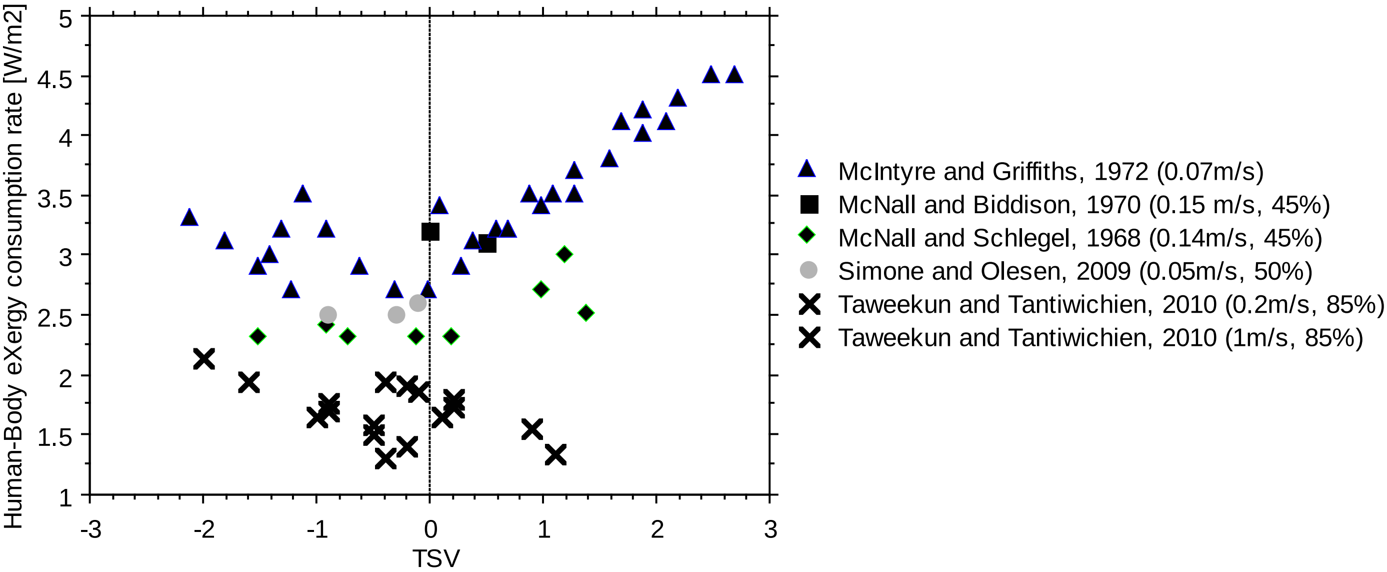

Figure 5: Human body exergy consumption rate as a function of TSV for different studies.

Looking more closely at the relative humidity, Figure 6 shows a decrease in the exergy consumption rate (until 1.3 W/m^2) with the increase in the relative humidity (at 80-90%) for the different experimental conditions.

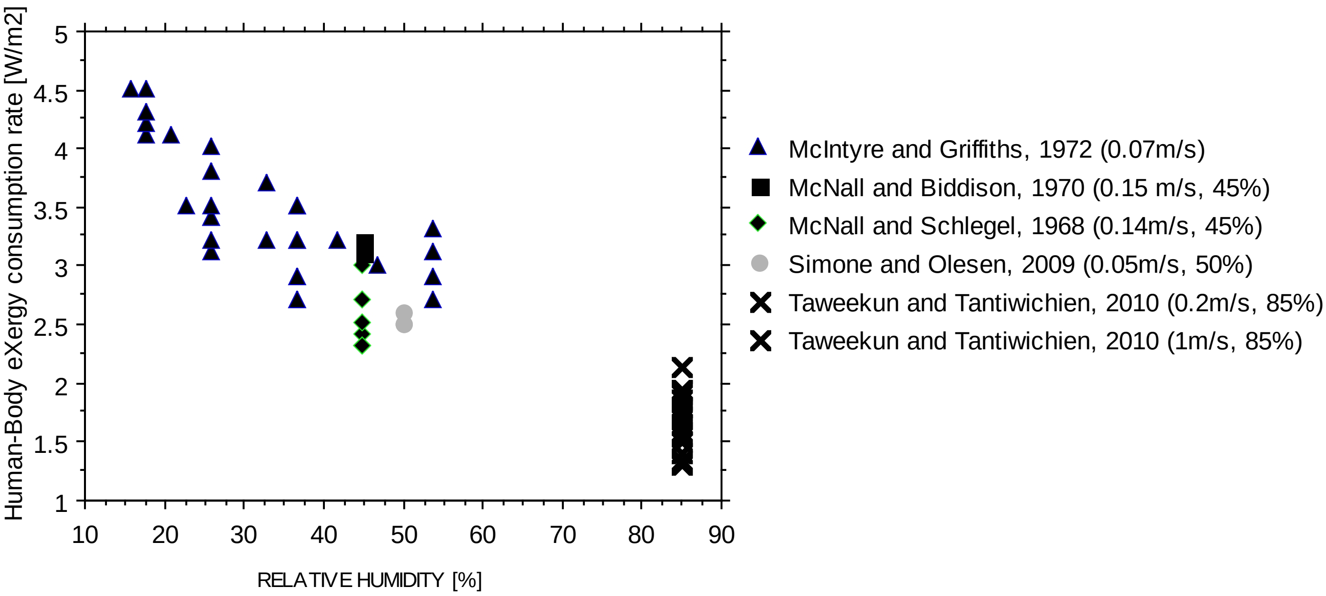

Figure 6: Human body exergy consumption rate as a function of relative humidity.

By plotting in the same graph the relation between the air and the mean radiant temperature with exergy consumption rate (see figure 4), it may be seen that there is a tendency for the exergy consumption rate to be low when the mean radiant temperature is higher than the mean air temperature. This tendency is supported by the relation between mean air and radiant temperature and the predicted mean vote.

In a real environment, in which indoor environmental conditions generally change during the day (due to changes in the outdoor climate and to intermittent solar radiation through the windows) even a small decrease of the mean radiant temperature can increase the exergy consumption rate (in particular, when the air temperature is lower than 23 °C). Nevertheless, an indoor environment controlled by a heating, ventilation and air conditioning (HVAC) system can maintain the condition with a lower exergy consumption rate.

Although the study indicates a tendency for the lowest human exergy consumption rates to occur when the air temperature is lower than the mean radiant temperature, more studies must be conducted and analysed for a better description of how the human exergy consumption varies as a function of thermal sensation.

5.2.5 Conclusion

The approach towards understanding the utilization of the exergy balance concept in relation to human thermal sensation is relatively new. It shows the lowest human body exergy consumption close to thermal neutrality, tending to a slightly cool side of thermal sensation.

When there are no data on thermal sensation, the operative temperature should be used to estimate the human body exergy consumption rate, as it accounts for both convective and radiant heat transfer between the human body and the surrounding environment. The few and different environmental conditions analysed in this work, as variables for evaluating the relationship between the thermal sensation votes and the human-body exergy consumption rates, suggest that more studies need to be conducted for implementing the results of the present approach.

Additional studies should estimate the major impact of subjective and environmental parameters, i.e. metabolic rate and humidity, on the human-body exergy consumption rate. In particular, studies should estimate the human-body exergy consumption rate for different climate regions (e.g. hot and humid regions, cold and dry regions).

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5.3 The effect of relative humidity on thermal comfort conditions from an exergy point of view

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5.3.1 Introduction

All natural or human processes, such as bio-chemical processes inside the human body or any technological process, present exergy-entropy processes. Their main characteristics are use of exergy, consumption of exergy, entropy generation and entropy disposal. The use of the exergy concept in the built environment in relation to thermal comfort is relatively new. Exergy analysis enables us to make connections among processes inside the human body and processes in a building (Shukuya and Hammache, 2002). Finally, it helps to create optimal thermal comfort conditions for everyone with a rational combination of passive and active technologies.

The relationship between the human-body exergy consumption rate, room air temperature and mean radiant temperature was first explored by Isawa and Shukuya (2002, 2003), Shukuya (2006) and furthermore elaborated upon by Prek (2004). Previous studies (Isawa and Shukuya, 2002, 2003; Shukuya 2006; Prek, 2004) show that the exergy consumption of the human body is lower if the subject is exposed to thermal comfortable conditions equal to thermal neutrality at an air temperature of 18-20ºC and a mean radiant temperature of 23-25ºC, especially under winter conditions (0 °C, 40% of relative humidity). The whole human-body exergy balance under typical summer conditions in hot and humid regions was analysed by Iwamatsu and Asada (2009), Shukuya (2008) and Shukuya et al. (2009).

The relation between the human-body exergy consumption rate and the human thermal sensation was first investigated by Simone and et al. (2010), who related thermal sensation data from earlier thermal comfort studies to the calculated human-body exergy consumption rate. The results showed that the minimum human body exergy consumption rate was related to the thermal sensation votes close to thermal neutrality, tending to the slightly cool side of thermal sensation. However, with the predicted mean votes index as an explaining variable, the relationship was different from the one observed when the thermal sensation votes were used. The minimal values of exergy consumption rate appear within the “cool” – “slightly warm” interval. By taking into consideration the influence of radiant heat transfer through the evaluated operative temperature range, the exergy consumption rate increases with the increase of the operative temperature above 24°C or when it decreases below 22°C.

So far, only the effects of different combinations of air temperatures and mean radiant temperatures have been studied, with constant relative humidity in experimental conditions. However, ASHRAE Standard 55 (2004) recommends that the relative humidity in the occupied spaces has to be controlled in the ranges from 30% to 60% for air temperatures between 20°C and 25°C. In hot and humid environments the values could differ from the recommended conditions. In some cases much lower or higher levels are defined. For example, air conditioning could be an important factor in patient therapy or in some instances also the major treatment (ASHRAE Handbook, 2007). For example, the ASHRAE Handbook defines: “ward for severe burn victims should have temperature controls that permit adjusting the room temperature up to 32°C and relative humidity up to 95%”.

The objective of the work presented in this section is to determine the effects of different levels of relative humidity, air temperature and mean radiant temperature on thermal comfort conditions from the exergy point of view and how the thermal comfort zone can be regulated from this perspective. The effect of different levels of relative humidity on the human body exergy balance, changes in human body exergy consumption rate and predicted mean vote (PMV) index (Fanger, 1970) were analyzed.

5.3.2 Methodologies

Input data

Subject characteristics			
Subjects	**Gender**	**Age [yr]**	**A_{du} (m^2)**
20	male	22.8+-2.6	1.89+-0.14
20	female	22.8+-2.6	1.89+-0.14

Experimental conditions						
RH [%]	**v_a [m/s]**	**T_a* [°C]**	**T_{mr}* [°C]**	**Metabolic rate [met]**	**Clothing [clo]**	**Mean skin humidity [%]**
50-80	0.1	25.0-25.5	25.0-25.5	1	0.63-0.9	33.7

*Table 1: Subject characteristics and experimental conditions. *Air temperature (T_a) and mean radiant temperature (T_{mr}) were almost equal.*

The performed analyses take into consideration the available data from the study by Toftum et al. (1998). They studied the effect of different fabric materials (cotton, microfiber, nylon, GoreTex) on the skin and of environmental temperature/clothing insulation together with perceived discomfort at a high level of skin humidity. The experiment was carried out in a climate chamber (3.6 x 4.8 x 2.6 m^3) in which the air temperature (T_a) and relative humidity (RH) were controlled. In total, 40 sitting subjects were exposed to different combinations of experimental conditions (Table 1).

Under experimental conditions, skin humidity was controlled with a combination of vapour permeability of the experimental clothing ensemble and the thermal environment. The relative skin humidity ranged from 32 to 75%, the skin wettedness from 0.09 to 0.48, and the moisture permeability from 0.12 to 0.40.

Case definition and experimental conditions for exergy analysis

Regarding the purpose of the study, two different human-body exergy analyses were carried out. These analyses considered the impact of interior microclimate conditions and individual parameters on separate components of human body exergy balance and thermal comfort. Table 1 presents the experimental conditions for the cases of both analyses (cases 1 and 2).

Case analysis	Clothing material	Moisture permeability [ ]	Air velocity [m/s]	Clothing resistance [Clo]	T_a [°C]	T_{mr} [°C]	RH [%]
1st analysis							
Case 1a	Cotton+ GoreTex	0.40	0.1	0.63	25.5	25.5	50
Case 1b	Cotton+ Micro fibre	0.32		0.90	25.0	25.0	80
Case 1c	Cotton+ PU nylon	0.12		0.89	25.0	25.0	50
Case 1d	Cotton+PU nylon	0.12		0.89	25.0	25.0	80
Case 1e	Cotton+PU nylon	0.12		0.89	25.5	25.5	80
2nd analysis							
Case 2a	Cotton+ GoreTex	0.40	0.1	0.63	15-35	15-35	30-96
Case 2b							
Case 2c							
Case 2d							
Case 2e							
Case 2f							

Table 2: Experimental conditions.

The studied conditions are summarized in Table 2. Cases 1a, 1b, 1c, 1d and 1e present the cases of the first analysis, where the effect of variations among clothing resistance, T_a and RH on human body exergy consumption was considered. The human body exergy calculation was done for average test subjects assuming that they are exposed to the same conditions inside the test space as the experimental study conducted by Toftum et al. (1998).

Cases 2a, 2b, 2c, 2d, 2e and 2f present the cases of the second analysis, where the effect of variations between T_a and RH on human body exergy consumption was studied. Air and mean radiant temperature varied from 15°C-35°C, RH from 30-96% and air velocity was constant at 0.1 m/s. For all calculations, the reference environmental temperature (the outdoor environmental temperature) and the outdoor RH were assumed to be equal to the indoor T_a and indoor RH. This assumption was made because no data were available regarding the outdoor conditions in the analyzed data from the Toftum et al. (1998). Furthermore, to assume the same conditions as in the Toftum et al. (1998), T_a was equal to T_{mr}.

Calculation of human body exergy consumption rate

For the purposes of this study, the human body is treated as a thermodynamic system based on exergy-entropy processes, consisting of a core and shell and situated in a test room with an environmental temperature. Individual thermal comfort conditions are analysed based on calculated human body exergy consumption rates and the predicted mean votes (PMV) index. The human body exergy consumption rates and PMV index were calculated with spreadsheet-based software developed by Asada (2008). The calculation procedures follow the human body exergy balance model used by Shukuya et al. (2009).

5.3.3 Results and discussion

Exergy balance equation for a human body

The general form of the exergy balance equation for a human body as a system is represented in equation (1) (Shukuya et al., 2010):

[exergy input] – [exergy consumption] = [exergy stored] + [exergy output] (1)

The exergy input consists of five components, as explained in item 5.1.3. of this book:

- warm exergy generated by metabolism;
- warm/cool and wet/dry exergies of the inhaled humid air;

- warm and wet exergies of the liquid water generated in the core by metabolism;
- warm/cool and wet/dry exergies of the sum of liquid water generated in the shell by metabolism and dry air to let the liquid water disperse;
- warm/cool radiant exergy absorbed by the whole skin and clothing surfaces.

The exergy output consists of four components:

- warm and wet exergy contained in the exhaled humid air;
- warm/cool and wet/dry exergy contained in resultant humid air containing the evaporated sweat;
- warm/cool radiant exergy discharged from the whole skin and clothing surfaces;
- warm/cool exergy transferred by convection from the whole skin and clothing surfaces into surrounding air (Shukuya et al., 2009).

To maintain healthy conditions (whereby the energy balance of the human body is within the healthy range of temperature and humidity) it is important that the exergy consumption and stored exergy are at optimal values with a rational combination of exergy input and output.

Results of 1st analysis

First, human body exergy balance results are presented for given conditions in Case 1a (Cotton*GoreTex, 25.5 °C, 50%, 0.63 Clo).

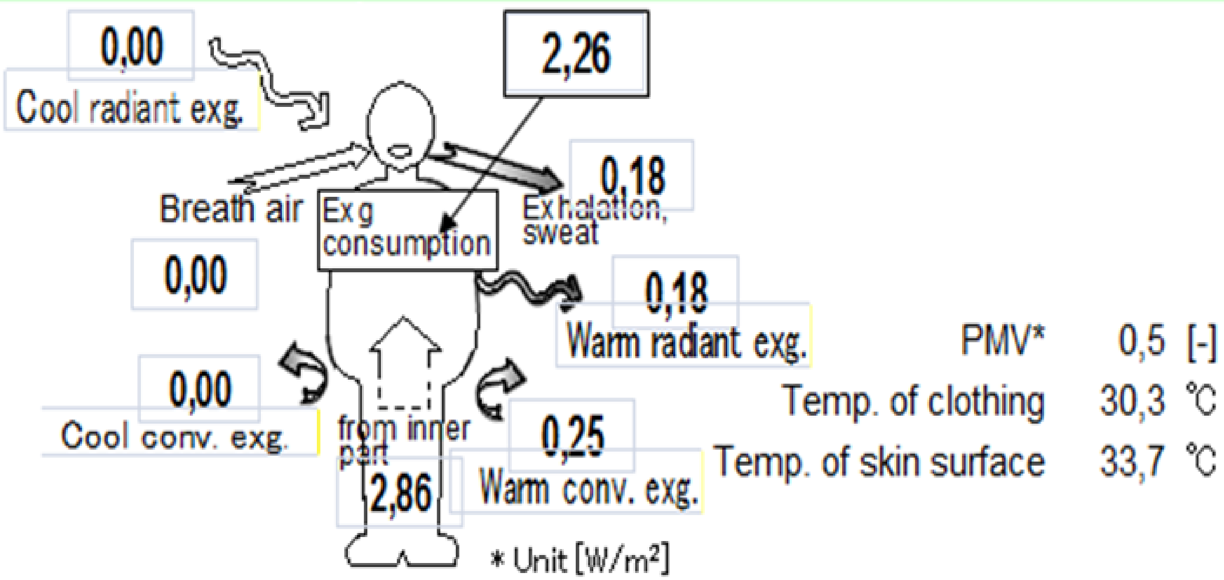

Figure 1: Exergy balance of the human body for Case 1a.

Figure 1 shows the numerical example of the whole human body exergy balance in the following conditions: 25.5 °C, 50% RH, 0.63 Clo. Input exergy represents thermal radiant exergy exchange between the human body and the surrounding surfaces and it influences thermal comfort. Cool radiant exergy absorbed by the whole skin and clothing surfaces is zero, because air temperature (T_a) is equal to mean radiant temperature (T_{mr}). Exergy of the inhaled humid air is also zero, because room RH and T_a are assumed equal to outside conditions. The main input exergy (100%) consists of warm exergy generated by metabolism. This means that 2.86 W/m^2 of thermal exergy is generated by bio-chemical reactions inside the human body. It is influenced by the difference between body core temperature and T_a. It is important to keep the body structure and function and to get rid of the generated entropy. Thus, 2.86 W/m^2 have to be released into ambient by radiation, convection, evaporation and conduction and represent output exergy. Because the room air relative humidity is below 100% RH (i.e. indoor air is not saturated), the water secreted from sweat glands evaporates into the ambient environmental space. Warm/cool and wet/dry exergy contained by resultant humid air containing the evaporated sweat is 0.18 W/m^2 (6.2% of output and stored exergies). In our case it appears as warm and wet exergy, because skin temperature is higher than T_a and skin RH is higher than room RH. Warm radiant exergy discharged from the whole skin and clothing surfaces emerges because of higher clothing temperature than T_a and represents 0.18 W/m^2 (6.2% of output and stored exergies). Exergy of 0.25 W/m^2 (8.6% of output and stored exergies) is transferred by convection from the whole skin and clothing surfaces into surrounding air, mainly due to the difference between clothing temperature and T_a. Exergy consumption that represents the difference between exergy input, exergy stored and exergy output is 2.26 W/m^2 (79% of output and stored exergies) for conditions in Case 1a.

If a test subject was exposed to conditions from Case 1b (Cotton+Microfibra, 25°C, 80% RH, 0.9 Clo), the input and output exergies would differ. Lower T_a causes lower internal metabolic heat production (due to smaller difference between T_a and body core temperature) and lower warm radiation and warm convection (due to smaller difference between clothes temperature and T_a). Higher humidity in Case 1b causes that the test subject cannot easily remove the resultant entropy by the evaporation of sweat. However, lower output and input exergies consequently result in lower exergy consumption rates in Case 1b (2.06 W/m^2).

As mentioned in the introduction, at thermal comfort conditions (PMV index close to 0) lower exergy consumption rates appear, when only the effect of temperature is taken into consideration. It is interesting that conditions in Case 1a are more comfortable (PMV index=0.5) with higher exergy consumption rate (2.26 W/m^2) than in Case 1b where PMV index is 1.4 and exergy consumption rate is 2.06 W/m^2. By taking this into consideration, it is very important to make an in-depth analysis of the whole human body exergy balance and to include the effect of RH (80% in Case 1b; 50% in Case 1).

Figure 2a presents exergy inputs and Figure 2b exergy outputs, exergy stored and exergy consumption for conditions in Case 1a. Exposure to different experimental conditions in Case 1b, 1c, 1d and 1e affects individual parts of the human body exergy balance. However, metabolic exergy production represents the only exergy input in all cases (100%) and varies from 2.42 W/m^2 in Case 1e to 3.07 W/m^2 in Case 1c (see Table 3). Table 3 gives the calculated values of the human body exergy consumption rate based on the experimentally studied Cases 1a-e.

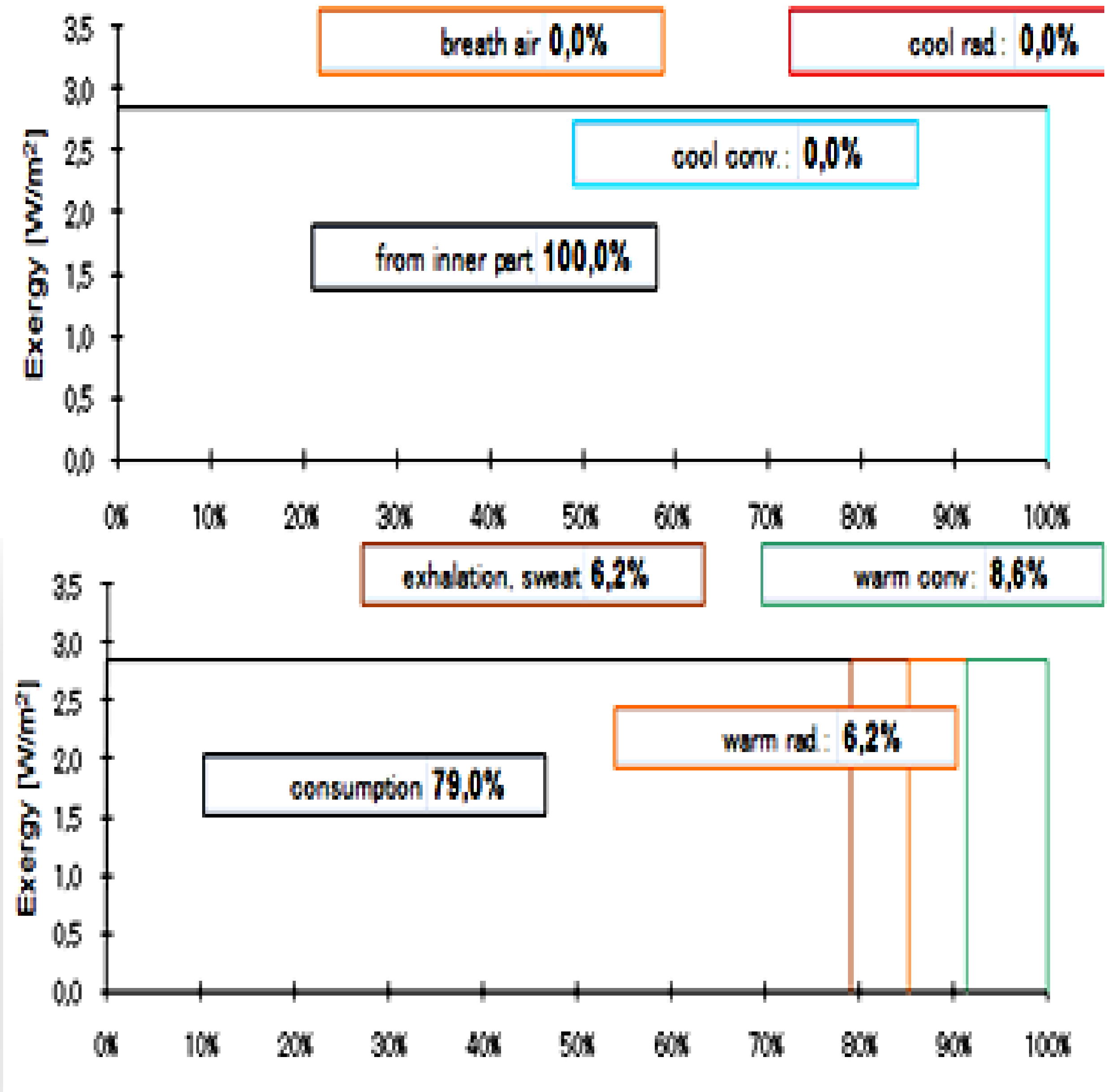

Figure 2: a) Exergy inputs (top) and b) exergy outputs, exergy stored and consumption (bottom) for conditions in Case 1a.

The exergy consumption rate represents the highest amount of output and stored exergy in all cases (79.0-83.4%). In general, the smaller the difference in temperature between the core and the shell of the human body is, the lower the exergy consumption rate is. The lowest exergy consumption rate appears in Case 1e (2.02 W/m^2) due to low metabolic production, output and input exergies. The highest rate appears in Case 1c (2.55 W/m^2), where metabolic exergy production, output and input exergies are higher due to higher RH.

RH has an important effect on the exergy consumption rate and PMV index. For example, the air temperature is in Case 1c and Case 1d the same (25.0°C). Higher RH in Case 1d (80%) causes a lower exergy consumption rate (2.06 W/m^2, fourth row in Table 3) and more discomfort conditions (PMV=1.4) than in Case 1c (at RH 50%) where exergy consumption rate is 2.55 W/m^2 (third row in Table 3) and PMV=0.9.

In Cases 1b, 1c and 1d there appear higher warm radiant exergy emission (5.7%, 0.14 W/m^2) and convective warm exergy transfer (5.7%, 0.20 W/m^2) because of a larger difference between clothes temperatures and T_a in comparison to Case 1e (4.6%, 0.13 W/m^2). Exhalation of sweat is 0.18 W/m^2 (3.6%) in Case 1a and 1c and 0.09 W/m^2 (6.2%) in Cases 1b, 1d and 1e due to the same T_a and RH conditions. Warm exergy transferred by convection is 0.20 W/m^2 in Case 1b, 1c, 1d (6.5%) and 0.25 W/m^2 (8.6%) in Case 1a.

Case	PMV index	Cool (C) / Warm (W) radiant exergy [W/m^2]	Breath air [W/m^2]	Exergy consumption [W/m^2]	From inner part [W/m^2]	Exhalation sweat [W/m^2]	Cool (C) / Warm (W) radiation [W/m^2]	Warm Convection [W/m^2]	Cool convection [W/m^2]
1a	0.5	W/C=0	0	2.26	2.86	0.18	W 0.18	0.25	0
1b	1.4	W/C=0	0	2.06	2.50	0.09	W 0.14	0.20	0
1c	0.9	W/C=0	0	2.55	3.07	0.18	W 0.14	0.20	0
1d	1.4	W/C=0	0	2.06	2.50	0.09	W 0.14	0.20	0
1e	1.4	W/C=0	0	2.02	2.42	0.09	W 0.13	0.13	0

Table 3: Results of the 1st analysis of human body exergy calculations.

Results of the 2nd analysis

The second analysis (Case 2a-f) examined the influence of different levels of relative humidity (30%-96%) and T_a=T_{mr} (15-35°C) on human body exergy consumption rates and PMV index. In case of 30% RH, 0.09 skin wettedness was assumed and in case of 96% RH, 0.48 skin wettedness was assumed.

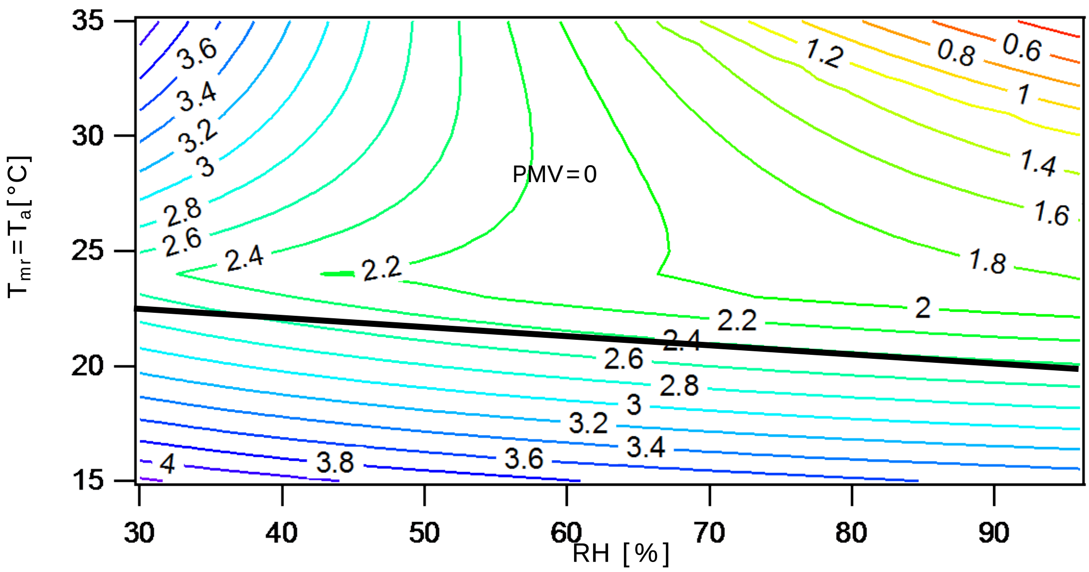

Figure 3: Human body exergy consumption rate [W/m^2] and predicted mean vote index in relation to T_a (=T_{mr}) [°C] and RH [%], Case 2a: 0.63 Clo, 1 Met, T skin=29.9-37.2°C, Tcore=36.9-38.0°C.

Figure 3 shows the relation between the exergy consumption rate, the PMV index (with T_a=T_{mr}), and RH for Case 2a. At cold and dry conditions (15°C Ta and RH 30%) the human body exergy consumption rate is the largest (4.23 W/m^2) due to the higher metabolic heat production, exhalation of sweat, radiation and convection. At hot and humid conditions (35°C, 96%) the human body exergy rate is minimal (0.288 W/m^2), mainly because of lower metabolic heat production, evaporation by sweat, warm and cool convection. High relative humidity causes higher skin wettedness (0.48) and enables the release of sweat from skin surface.

Hot and dry conditions (35°C and 30%) and cold and dry conditions (15°C and 30%), result in similar high exergy consumption rates. The difference appears if the whole human-body exergy is taken into consideration. High temperature and low RH causes lower internal heat production by metabolism. It should be emphasised that at higher temperatures lower values of sweat losses, warm radiation and cool convection appear, even if RH is the same. In cold and humid conditions higher internal heat production by metabolism and a higher amount of output exergy by sweat, warm radiation and cool convection appear.

Table 4 presents the results of the human body exergy balance and PMV index in extreme conditions (hot/cold; humid/dry).

As mentioned in item 5.3.1, studies (Isawa and Shukuya, 2002, 2003; Shukuya 2006; Prek, 2004) have shown that for conditions of human body thermal comfort, where only the effect of temperature is taken into consideration, exergy consumption is minimal. However in the present study, where also the effect of relative humidity was taken into consideration, higher human body exergy consumption appears at thermal comfort conditions (PMV index close to 0). This is because there is some inevitable chemical exergy consumption inside the human body, which causes the generation of quite a large amount of entropy that has to be discarded. Otherwise the human body cannot maintain its health.

Case	Conditions	PMV index	Cool (C) / Warm (W) radiant exergy [W/m^2]	Breath air [W/m^2]	Exergy consumption [W/m^2]	From inner part [W/m^2]	Exhalation sweat [W/m^2]	Cool (C) / Warm (W) radiation [W/m^2]	Warm Convection [W/m^2]	Cool convection [W/m^2]
2a	15°C 30%	-1.4	W 0 C 0	0	4.230	6.070	0.518	W 0.524	0	0.800
2b	35°C 80%	3.0	W 0 C 0	0	0.8317	0.9282	0.009	W 0.0065	0	0.0084
2c	35°C 96%	3.0	W 0 C 0	0	0.288	0.521	0.002	W 0.012	0	0.015
2d	35°C 30%	2.4	W 0 C 0	0	4.137	4.295	0.155	W 0.0007 32	0	0.001
2e	15°C 80%	-1.3	W 0 C 0	0	3.634	5.244	0.261	W 0.536	0	0.812
2f	15°C 96%	-1.2	W 0 C 0	0	3.526	5.103	0.222	W 0.539	0	0.816

Table 4: Results of the 2nd analysis of human body exergy calculations for extreme conditions.

For example in Case 2f (T_a 15°C and RH 96%) the human body exergy consumption is 3.526 W/m^2 and the PMV index is -1.3. The lowest possible exergy consumption rate (0.288 W/m^2) appears in Case 2c (T_a 35°C and RH 96%) where most people feel uncomfortable (PMV index=3.0). However, the PMV index is 0 in the range of T_a equal to 22-24°C, independently of RH, as it is shown in Figure 3. The same conclusion was reached in the study by Koch et al. (1960), where humidity had a negligible effect on thermal comfort up to 60% RH and 18°C. Below these levels T_a alone was the governing factor. In extreme conditions, such as a hot and dry environment (35°C and 30%) and cold and dry environment, (15°C and 30%) the values of exergy consumption are very similar (4.230 W/m^2 - Case 2a and 4.137 W/m^2 – Case 2d).

The difference appears if all terms of the exergy balance are taken into consideration. From this point of view, it is very important to make an in-depth analysis of all exergy inputs and outputs. A new possibility of active regulation of human body exergy consumption and creation of thermal comfort conditions for all users is revealed and will present the basis for our future work. More studies are needed in order to define human exergy consumption as a function of the thermal sensation and RH. Operative temperature should be used to estimate the human body exergy consumption rate and RH. Additional calculations should be carried out with respect to $T_a \neq T_{mr}$, outside ≠ inside conditions.

5.3.4 Conclusions

From the above discussion the following conclusions about the human body exergy consumption and thermal comfort conditions can be derived:

- calculations of human body exergy consumption rates enable us to see more precisely how much a subject produces and gives away the heat depending on different environmental conditions;

- past studies showed that in the framework of thermal comfort conditions only the effect of temperature was taken into consideration, while exergy consumption was minimal. The present study shows that relative humidity has an important effect on thermal comfort and may affect exergy consumption;

- RH in combination with air temperature has an important effect on thermal comfort conditions and human body exergy consumption rate, especially in extreme conditions;

- at hot and dry conditions the human body exergy consumption rate is the largest, at hot and humid conditions it is minimal. Hot and dry and cold and dry conditions have similar exergy consumptions rates. The difference appears if the whole human body exergy balance chain is taken into consideration;

- to maintain comfortable conditions it is important that exergy consumption and stored exergy are at optimal values with a rational combination of exergy input and output.

Acknowledgement

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5.4 Comparison between conventional and LowEx systems from the aspects of individual users, building energy use and various environmental conditions

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5.4.1 Introduction

For sustainable future buildings with attained 20% goal by EPBD Directive 2010/31/EU, a new approach of solving problems related to high energy use has to be revealed. A study of exergy consumption patterns for space heating in Slovenian buildings (Dovjak et al., 2009) shows that the most effective solution is a holistic approach including improvements of both building envelope and boiler efficiency. However, besides that also health and comfort conditions for individual users have to be attained. With regard to the latter, the possibility has to be well considered of designing heating and cooling systems based on individual user needs besides rational building energy use.

Exergy analysis can treat processes in a building jointly with processes inside the human body (Shukuya and Hammache, 2002). Highly satisfied users and the attained minimal possible energy use for heating and cooling purposes assure that low exergy systems for heating and cooling (hereafter LowEx systems) are favoured above conventional ones. LowEx systems provide heating or cooling energy at a temperature close to room temperature and have been applied to numerous public and residential buildings, both new and old. The main reason has been their advantages in comparison to conventional systems for heating and cooling, such as improvement of comfort conditions, decrease of energy use for heating and cooling of buildings and improved indoor air quality (Olesen 1997, 1998; Shukuya and Hammache, 2002; Shukuya 2006; Shukuya et al. 2010; Krainer et al., 2007).

Experiences of architects and engineers working with the design of comfort conditions in winter show that higher surface temperature (T_{mr}) and lower air temperature (T_a) can result in more comfortable conditions. This coincides with the fact that comfort conditions seem to lead to lower exergy consumption of the human body. The relationship was first investigated by Isawa et al. (2003), Shukuya (2006) and further researched by Prek (2004). Simone et al. (2010)

studied the relation between the human-body exergy consumption rate and the human thermal sensation. Results of Simone et al. (2010) showed that the minimum human body exergy consumption rate was related to the thermal sensation votes close to thermal neutrality, tending to the slightly cool side of thermal sensation. The whole human-body exergy balance under typical summer conditions in hot and humid regions was analyzed by Iwamatsu and Asada (2009) and Shukuya et al. (2010).

So far only the exergy consumption of an average man in normal conditions has been considered, but not of individual users in different environments (i.e. hot/humid, cold/humid, hot/dry, cold/dry). From the exergetic point of view, the comparison between conventional and LowEx systems regarding thermal comfort conditions for individual users in normal and extreme conditions and building energy use was investigated by the authors, as reported in this section. This allows active regulation of the thermal comfort zone for individualized users to be designed and harmonized with attained minimal possible energy use.

5.4.2 Methodologies

The test room (9.0 x 4.0 x 4.0 m^3) is located at the Chair for Buildings and Constructional Complexes, Faculty of Civil and Geodetic Engineering, University of Ljubljana. It is equipped with a LowEx system and a conventional system with time separation. The conventional system includes 3 oil filled electric heaters and an AC device. The LowEx system includes six low temperature heating and high temperature cooling ceiling radiant panels. For the purpose of our experiment, 9m^2 of ceiling was covered with panels. In the test room T_a and T_{mr} differ in the range of 15-35°C and the relative humidity varies from 30 to 96%. Two test subjects were assumed for the simulation of the human body exergy balance calculation (Table 1). Individual input data were collected from the relevant literature (Simmers, 1988; LeDuc et al., 2002; ISO 7730:2005; ISO 8996:2004; Fanger, 1970; ASHRAE, 1977). Energy use for heating and cooling, T_{out}, T_a, T_{mr}, RH_{in} and RH_{out} was continuously monitored for both systems.

Subject characteristics				
Subjects	**Metabolic rate [met]**	**Clothing [clo]**	**T_{skin} [°C]**	**$T_{body\ core}$ [°C]**
A	1.1	0.6	34.3	36.9
B	2	0.6	36.3	37.3

Experimental conditions			
RH [%]	**v_a [m/s]**	**T_a [°C]**	**T_{mr} [°C]**
30 – 96	0.1	15.0 - 35.0	15.0 - 35.0

Table 1: Subject characteristics and experimental conditions.

For the purpose of periodical monitoring and control of indoor parameters an integrated control system of internal environment on the basis of fuzzy logic was used. Individual thermal comfort conditions were analyzed by calculated human body exergy consumption rates and predicted mean votes (PMV) index with spread sheet software developed by Hideo Asada Rev 2010 (Iwamatsu and Asada, 2009). The calculation procedures follow the human body exergy model by Shukuya et al. (2010).

The human body is treated as thermodynamic system of core and shell, based on exergy-entropy processes. For exergy calculations, the reference environmental temperature (the outdoor environmental temperature) and the outdoor RH were assumed to be equal to the indoor T_a and indoor RH.

5.4.3 Results and discussion

All natural or human made processes, such as bio-chemical processes inside the human body or any technological process, present exergy-entropy processes. Their main characteristics are generation of exergy, consumption of exergy, entropy generation and entropy disposal. The general form of the exergy balance equation for a human body as a system is expressed as follows (Shukuya et al, 2010), as explained in item 5.1.3. of this book:

[exergy input] – [exergy consumption] = [exergy stored] + [exergy output] (1)

Where the exergy input consists of five components:

- warm exergy generated by metabolism;
- warm/cool and wet/dry exergies of the inhaled humid air;
- warm and wet exergies of the liquid water generated in the core by metabolism;
- warm/cool and wet/dry exergies of the sum of liquid water generated in the shell by metabolism and dry air to let the liquid water disperse;
- warm/cool radiant exergy absorbed by the whole skin and clothing surfaces.

and exergy output consists of four components:

- warm and wet exergy contained in the exhaled humid air;
- warm/cool and wet/dry exergy contained in resultant humid air containing the evaporated sweat;

- warm/cool radiant exergy discharged from the whole skin and clothing surfaces;
- warm/cool exergy transferred by convection from the whole skin and clothing surfaces into surrounding air (Shukuya et al., 2010).

To maintain healthy conditions it is important that exergy consumption and stored exergy are at optimal values with a rational combination of exergy input and output.

Human body exergy consumption and PMV index in normal conditions

Table 2 presents the comparison between a LowEx and a conventional system in normal room conditions. Human body exergy consumption rates and PMV index are calculated for two subjects exposed to different combinations of T_a and T_{mr} that result in the same operative temperature 22.5°C. RH is assumed to be 60%. The data show that the human body exergy rates and PMV index vary among individuals for both systems, even if they are exposed to the same environmental conditions. Better comfort conditions are created in the room with a LowEx system, where higher surface than air temperatures (T_{mr} 27° C; T_a 18°C) are reflected in more comfortable conditions (PMV= -0.14, 0.08).

Subject	**T_a[°C]**	**T_{mr}[°C]**	**PMV index**	**Exergy consumption rate [W/m^2]**
RET system				
A	18.0	27.0	-0.14	2.23
B			0.08	5.69
A	27.0	18.0	-0.16	2.78
B			0.45	5.56
Conventional system				
A	22.5	22.5	-0.16	2.38
B			0.25	5.50

Table 2: Comparison between LowEx system and conventional system.

The following is an analysis of the separate parts of the human body exergy balance for subjects A and B exposed to normal conditions in a room with conventional and LowEx systems.

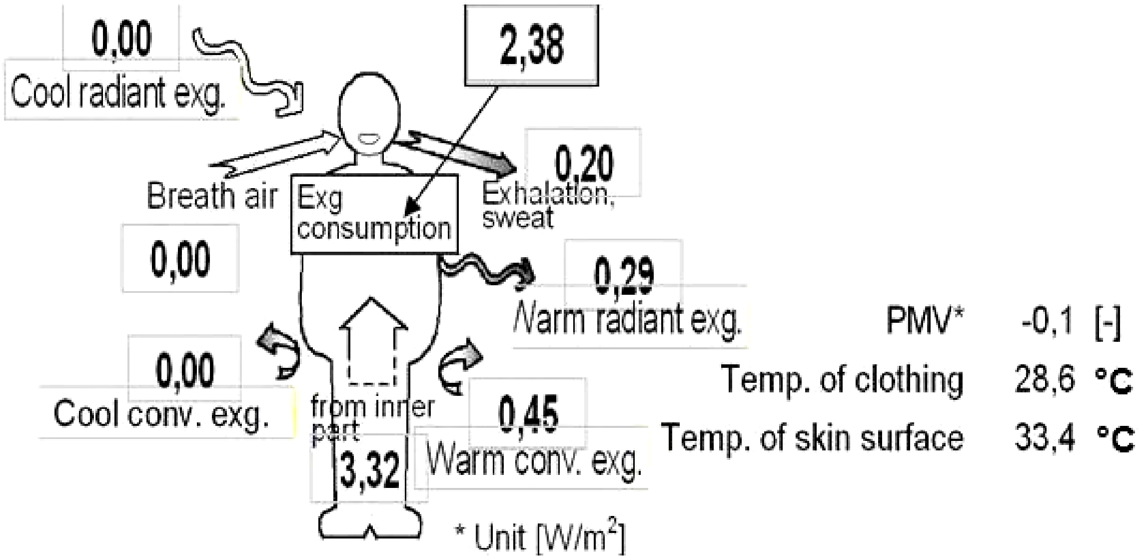

Figure 1: Exergy balance of the human body for Subject A in a room with a conventional system (22.5 °C T_a and 22.5 °C T_{mr} , 60% RH).

Figure 1 shows a numerical example of the whole human body exergy balance for Subject A in a room with a conventional system (22.5 °C T_a, 22.5 °C T_{mr}, 60% RH). Outnput exergy represents thermal radiant exergy exchange between the human body and the surrounding surfaces it has a large influence on thermal comfort. Cool radiant exergy absorbed by the whole skin and clothing surfaces is zero, because T_a is equal to T_{mr}. Exergy of the inhaled humid air is also zero, because room RH and T_a are assumed equal to outside conditions. The main input exergy to the skin (100%) is represented by warm exergy generated by metabolism in the body. This means that 3.32 W/m^2 of thermal exergy is generated by bio-chemical reactions inside the human body. It is influenced by the difference between body core temperature and T_a. It is important to keep the body structure and function and to get rid of the generated entropy. Thus, 3.32 W/m^2 have to be released into the ambient by radiation, convection, evaporation and conduction, representing output exergy. Because the relative humidity of the room air is less than 100% (i.e. the air is not saturated), the water secreted from sweat glands evaporates into the ambient environmental space. Warm/cool and wet/dry exergy of the humid air containing the evaporated sweat is 0.20 W/m^2 (6.1% of output and stored exergies). In this case it appears as warm and wet exergy, because the skin temperature is higher than T_a and skin RH is higher than room RH. Consequently, warm radiant exergy is discharged in the enclosure from the whole skin and clothing surfaces with the amount of 0.29 W/m^2 (8.6% of output and stored exergies). Also, exergy amounting to 0.45 W/m^2 (13.5% of output and stored exergies) is transferred by convection. Exergy consumption representing the difference between exergy input, exergy stored and exergy output is 2.38 W/m^2 (71.7% of output and stored exergies) for Subject A in a room with a conventional system (22.5 °C T_a, 22.5 °C T_{mr}, and 60% RH).

The whole human body exergy balance for Subject B in a room with a conventional system differs from that for Subject A. A higher metabolic level (2 Met) results in: doubled values of warm exergy generated by metabolism (6.86 W/m^2) and exergy consumption rate (5.50 W/m^2); higher values of warm convection (0.73 W/m^2) and exhalation of sweat (0.37 W/m^2); and lower warm radiation (0.26 W/m^2).

When Subject A is exposed to other conditions in the room with the LowEx system (18.0°C T_a, 27.0°C T_{mr}, 60% RH) resulting in the same operative temperature (22.5°C) as in the room with a conventional system, the whole human body exergy balance differs. 4.28 W/m^2 (87.6%) of warm exergy is generated by metabolism and 0.61 W/m^2 (12.4%) of warm radiant exergy represents output exergy. Higher T_{mr} than T_a results in higher warm radiant exergy (0.91 W/m^2, 18.6%), warm convection (1.44 W/m^2, 29.6%), a little higher exhalation of sweat (0.30 W/m^2, 6.0%) and lower exergy consumption (2.23 W/m^2, 45.7%) than in a room with a conventional system. For Subject B the same conclusions could be drawn as for Subject A: higher metabolic rate results in higher values of warm exergy generated by metabolism (8.44 W/m^2), exergy consumption rate (5.69 W/m^2), warm convection (2.10 W/m^2), exhalation of sweat (0.54 W/m^2) and warm radiation (0.72 W/m^2) than in the room with a conventional system. The difference between T_{mr} and T_a results in 0.61 W/m^2 of warm radiant exergy as input exergy.

Human body exergy consumption and PMV index in extreme conditions

Thermal comfort conditions do not always result in lower human body exergy consumption rates, as demonstrated by Isawa et al. (2003). RH has an important effect on human body thermal perception. In-depth analysis of the whole human body exergy balance terms shows how individual human bodies release the heat and also the effects of different levels of RH. The influence of different levels of relative humidity (30%-96%) and T_a=T_{mr} (15-35°C) on human body exergy consumption rates and PMV index was analyzed by performing calculations for subjects A and B exposed to extreme conditions (i.e. hot/humid, cold/humid, hot/dry, cold/dry), In conditions of 30% or 96% of relative humidity, 0.09 or 0.48 skin wettedness were respectively assumed. Figure 2 represents the relation between the exergy consumption rate, the PMV index with T_a=T_{mr}, and RH for Subject A. In hot and dry conditions (35°C T_a and 30% RH) the human body exergy consumption rate is the highest (4.54 W/m^2) due to the higher metabolic production, exhalation of sweat and lower radiation and convection. In hot and humid conditions (35°C, 96%) the human body exergy consumption rate is minimal (0.33 W/m^2). This is mainly because of lower metabolic heat production, evaporation by sweat, higher warm radiation and warm convection than in hot and dry conditions.

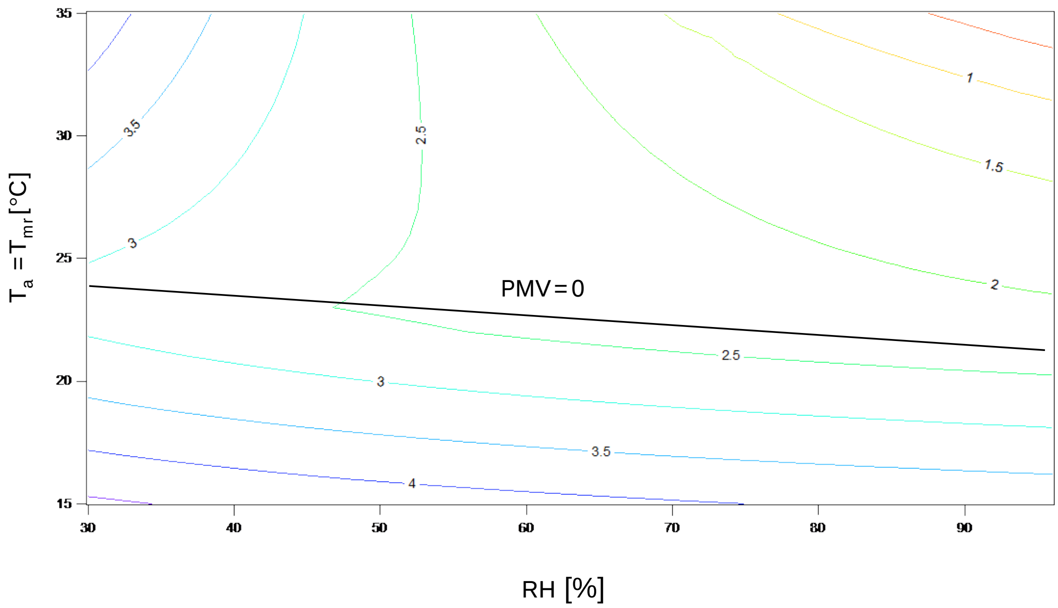

Figure. 2: Human body exergy consumption rate [W/m^2] and predicted mean vote index in relation to T_a (=T_{mr}) [°C] and RH [%], Subject A.

High relative humidity causes higher skin wettedness (0.48) and enables the release of sweat from the skin's surface. Hot and dry conditions (35°C and 30% RH) and cold and dry conditions (15°C and 30% RH) result in similar exergy consumption rates. The difference appears, if the whole human-body exergy balance is taken into consideration. High temperature and low RH cause lower internal heat production by metabolism. It should be emphasized that at higher temperatures lower sweat loss, warm radiation and warm convection occur, even if the RH is the same.

In cold and humid conditions there is higher internal heat production by metabolism and higher exergy output by sweat, warm radiation and convection. When Subject B is exposed to extreme conditions, the difference among separate parts of human body exergy balance becomes more significant. However, the highest consumption rate appears in hot and dry conditions (8.25 W/m^2).

Table 3 presents the results of the human body exergy balance and PMV index in extreme conditions (hot/cold; humid/dry). As mentioned in item 5.4.1, studies (Isawa et al., 2003; Shukuya, 2006; Prek, 2004; Simone et al. 2010) show that exergy consumption is minimal in the framework of thermal comfort conditions of the human body where only the effect of temperature is taken into consideration. In the present study the effect of relative humidity is also taken into consideration, and higher human body exergy consumption occurs at thermal comfort conditions (PMV index close to 0). This is because there is some inevitable chemical exergy consumption inside the human body, which causes the generation of quite a large amount of entropy that has to be discarded. Otherwise the human body cannot maintain its health. For example, in a hot/dry condition (35°C, 30% RH) the human body exergy consumption rate is 4.54 W/m^2 (PMV index 2.8) for Subject A and 8.25 W/m^2 (PMV 2.3) for Subject B. The lowest possible exergy consumption rate (0.73 W/m^2, 0.33 W/m^2) occurs in hot/humid conditions (35°C, 96% RH) where most people feel uncomfortable (PMV index 2.4 and 2.9). However, the PMV index is 0 in the range of T_a 22-24°C, independently of RH (Figure 2). Koch et al. (1960) concluded that humidity had a negligible effect on thermal comfort up to 60% RH and up to 18°C. Below these levels T_a alone was the governing factor. From this point of view, it is very important to make an in-depth analysis of all exergy inputs and outputs.

Subject	**T_a=T_{mr} [°C]**	**RH [%]**	**PMV index**	**Exergy consumption rate [W/m^2]**
A	35	30	2.8	4.54
	15	30	-1.2	4.42
	35	96	2.9	0.33
	15	96	-1.1	3.71
B	35	30	2.3	8.25
	15	30	-0.8	6.72
	35	96	2.4	0.73
	15	96	-0.8	5.66

Table 3: Results of human body exergy calculations for extreme conditions.

Energy use for heating and cooling

Energy use was measured for the same space equipped with LowEx and conventional systems in different periods. Hence, approximately the same conditions were selected for comparing the systems (equal set-point T, time period, air supply temperature T_{out} and T_a outdoor vary among systems by ± 0.5°C; 0.4% assumed error). The measured hourly energy use for heating was 11.0-26.8% lower for the LowEx system than for the conventional system. The hourly energy use for cooling was 41.2-61.5% lower for the LowEx system. For the whole measured cooling period (187 cooling hours) the energy use for the LowEx system is 0.32 kWh, and for conventional system 0.84 kWh. The reason behind the low effectiveness of the LowEx system during the heating period is the relatively low surface area of the panels (i.e. 25% of the ceiling surface). The calculated energy use for heating in case of a fourfold increase in panel surface area is 40% lower than for the conventional system.

Active regulation of thermal comfort zone

The LowEx system enables active regulation of human body exergy consumption rates, by changing the settings of T_{mr} and T_a (from one zone to another) for every individual separately. This can be done without deterioration of one's comfort conditions (Fig. 3). For example, if the LowEx system was set up to T_a 20°C, T_{mr} 17°C, this could result in higher human body exergy consumption rate valid for thermoregulation (5.3 W/m^2, PMV=0, zone A) compared to the conditions created if the LowEx system was set up to T_a 17°C, T_{mr} 25°C (4.9 W/m^2, PMV=0, zone B). In such way, a personalized climate is designed. And, even more, lower air temperatures lead to lower energy use.

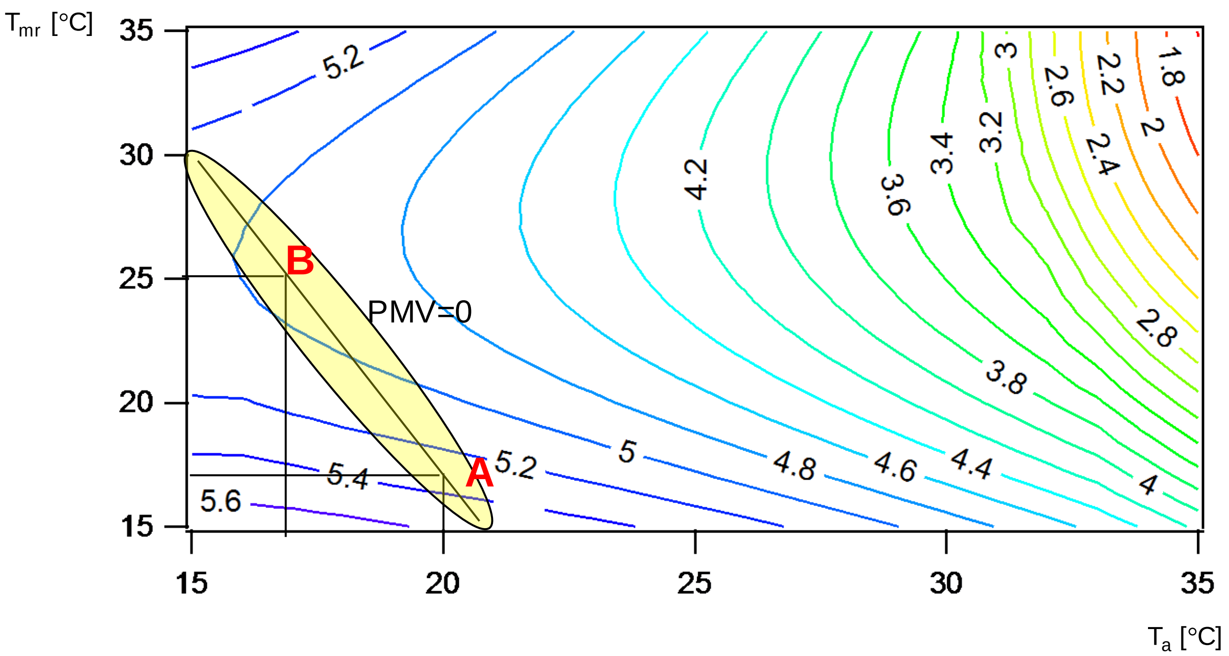

Figure 3: Active regulation of thermal comfort zone, Subject B, LowEx system.

5.4.4 Conclusions

Results of the study on individual test subjects in normal room conditions show that the human body exergy consumption rates and PMV index vary among individuals for conventional and LowEx systems, even when they are exposed to the same environmental conditions. Better comfort conditions are created in the room with the LowEx system, where surface temperatures higher than air temperatures are reflected in PMV closer to 0. Results of calculated individual human body exergy consumption and PMV index in extreme conditions show that in hot and dry conditions the human body exergy consumption rate is the highest, while in hot and humid conditions it is the lowest. Similar human body exergy consumption rates appear in hot and dry and also in cold and dry conditions. The difference appears if the whole human body exergy balance terms are taken into consideration. LowEx systems enable regulation of the human body exergy consumption, health and comfort conditions at the same time. The measured hourly energy use for heating/h was 11.0-26.8% lower for the LowEx system than for the conventional system. The hourly energy use for cooling was 41.2-61.5% lower for the LowEx system.

Acknowledgement

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5.5 Human thermal comfort in environments with moderately drifting operative temperatures – state of the art

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5.5.1 Introduction

According to the International Energy Agency (ECBCS, 2002), approximately one third of the world's consumption of primary energy takes place in non-industrial buildings, where it is utilized for heating and cooling, lighting and the operation of appliances. This implies that there is a need to find new ways of heating, ventilation and air conditioning (HVAC) system design and operation that can reduce the energy demand of such a system. Some of the design concepts that are used today result in moderate operative temperature drifts. These concepts include application of an alternative control strategy, which allows the indoor temperatures to drift within the borders of a comfort zone. This means substantial energy savings in comparison to keeping constant temperatures. In addition, the installed system capacity can be reduced.

Radiant cooling and heating of office buildings with water circulated in a system of pipes embedded in concrete slabs between storeys (Thermo Active Building Systems, TABS) became popular in the beginning of the nineties (Meierhans 1993; Olesen and Dossi 2004). These systems allow separation of climate control and ventilation because heat or cooling loads are extracted mainly by means of radiant heat transfer. During the summer season, thermal mass of the building is cooled down at night when outdoor temperatures are low. Consequently, heat loads are absorbed during the day reducing the need for mechanical cooling.

Another advantage of the system is that the temperature of the cooling/heating water may be kept close to the room temperatures, which gives a possibility to utilize renewable energy sources (heat pumps, ground heat exchangers etc.). The operation of TABS leads to operative temperature drifts usually up to 0.5 K/h (De Carli and Olesen 2001). Moreover, in non-air-conditioned or naturally ventilated buildings, and in buildings that passively utilize thermal mass and night cooling, indoor operative temperatures may drift upwards slowly during the day. In winter, also downward drifts occur when thermal mass (heated during the night) is cooled during the day covering heat losses of the building.

The systems mentioned above are able to provide certain energy savings, but not only energy savings are an important issue during design of office buildings. The indoor environment has been shown to have a clear impact on the occupants. If the occupants are exposed to unacceptable/unpleasant conditions, their mental performance and productivity can be affected. Their health, comfort and performance should not suffer from the benefits of energy consumption reduction.

This section reviews available literature concerning the investigation of the effect of drifting temperatures on humans. Moderate temperature drifts were studied only in climate chambers where experimental subjects assessed their thermal comfort using standardized questionnaires. In the studies air quality, SBS symptoms and productivity were investigated. Subjects were exposed only to constant thermal environments (at different levels of temperature or humidity) or to cyclic temperature changes around the preferred ambient temperature. There are only three very recent studies (outlined below in item 5.5.2) that investigated human responses to moderate temperature drifts together with the productivity.

5.5.2 Climate Chamber Experiments

The effects of various rates of temperature change for 3 different levels of clothing were investigated in the study of Berglund and Gonzalez (1978a). Twelve test subjects wore clothing corresponding to 0.5, 0.7 and 0.9 clo and experienced 7 rates of temperature change: 0, ±0.5, ±1 and ±1.5 K/h. A dew point of 12°C was kept constant during all experimental conditions while each of them lasted for 4 hours. Subjects provided their own clothing, which they selected to conform to the list given by researchers for each test condition. An activity level of the subjects was kept at approx. 1.2 met.

The different clothing insulation levels had only a small effect on the responses of the subjects who were exposed to the constant temperature. The responses to the temperature ramp of +0.5 K/h were nearly identical to those obtained for the constant temperature. When the subjects were exposed to temperature ramps of ±1 and ±1.5 K/h, their thermal sensation and their thermal acceptability increased/decreased linearly with the temperature (depending on the direction of the ramp). However, this increase was observed with approximately one hour delay from the onset of the ramp. The authors concluded that ramps of +0.5 K/h were indistinguishable from the constant environment within the range of temperatures from 23°C to 25°C for decreasing ramps and from 25°C to 27°C for increasing ramps. This was limited for sedentary persons wearing normal indoor clothing. Thermal response lags appeared to be less consistent for steeper decreasing ramps (-1, -1.5 K/h) than for steeper increasing ramps (+1, +1.5 K/h), indicating that subjects were more sensitive to decreasing temperatures. The thermal sensitivity, calculated as the ratio between the change in the thermal sensation and the corresponding change in the temperature itself ($\Delta TS/\Delta T$), was calculated from the data obtained. It showed that subjects wearing clothing of 0.5 clo were less sensitive to the faster changing environments in both directions. With higher clo values, differences in sensory responses due to the rate of temperature change were smaller.

Another study concerning human thermal comfort under non-steady conditions was conducted by Knudsen et al. (1989). Temperature ramps of ±1 K/h and ±5 K/h were studied. The temperature was increased during periods between 1.5 and 3 hours (depending on the slope of the ramp). Subjects used the same clothing ensemble for each of the seven experiments. On average, the clothing insulation was 0.8 clo and the average activity level of all subjects was approximately 1.2 met. The absolute humidity was kept constant during all exposures (the partial water vapour pressure in the air was 1.28 kPa). At the beginning of the experiment, a temperature corresponding to a “neutral” thermal sensation was determined. The “neutral” temperature obtained was 21.5 °C and all four tested ramps started at that temperature. Other steady-state mean thermal sensations were found from exposures to constant temperatures of 19.5 °C and 23.5 °C. The mean thermal sensation votes obtained by exposing subjects to the constant temperature were later compared to the mean thermal sensation votes obtained for the same temperature levels but reached by the ramp.

Thermal sensation data for all tested ramps were found to be on the same straight line and to coincide with "baseline" steady-state values (Figure 1). Thermal acceptability at the same temperature was generally higher at the faster ramps (Figure 2). The acceptability ratings corresponding to the same thermal sensation were lower for the ramps of ±1 K/h than for ramps of ±5 K/h. This indicated that subjects perceived faster rates of temperature change as more acceptable than slow rates.

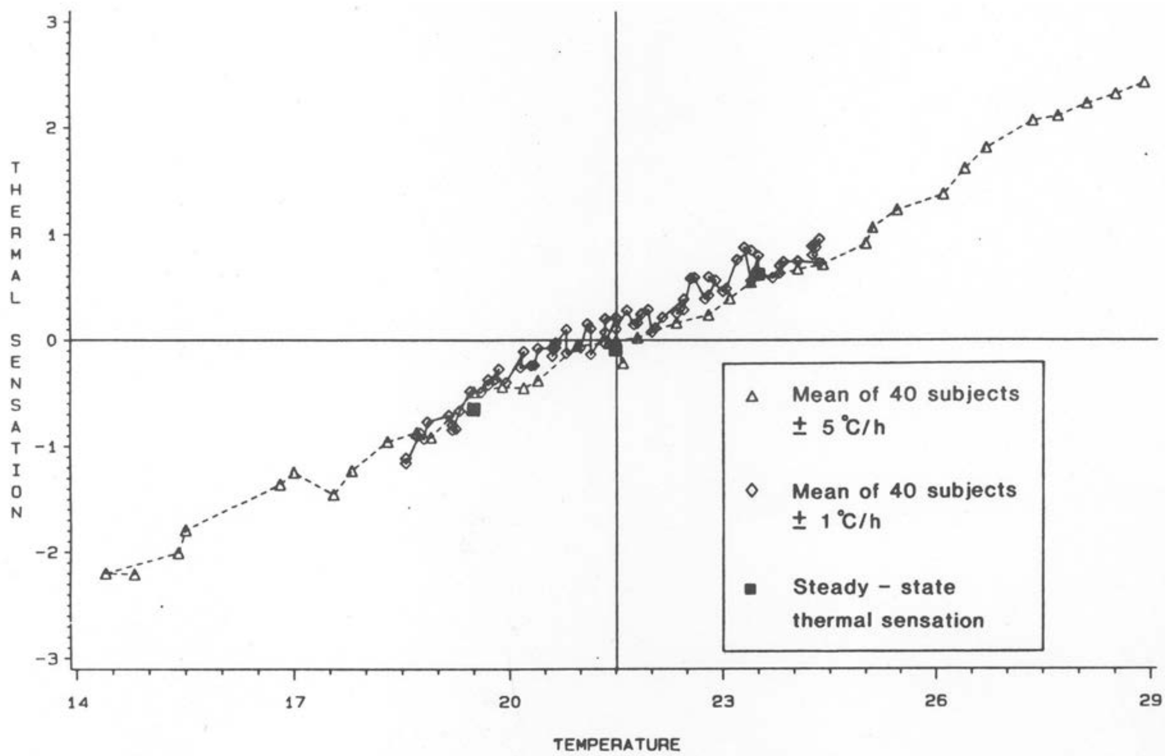

Figure 1: Adjusted thermal sensation votes as a function of increasing operative temperature (Knudsen et al. 1989)

A comparison of the relationship between thermal sensation and thermal acceptability as observed in the experiments and as predicted by thermal comfort model by Fanger (1970) is also depicted in Figure 2. The mean values of thermal acceptability for corresponding thermal sensations were lower than those predicted by the model in the case of decreasing temperature ramps. However, those obtained for faster increasing ramps corresponded quite well with predictions made with the model developed and intended for use mostly under steady-state conditions. Mainly because of that, Knudsen et al. (1989) concluded that it would be possible to use the PMV model to predict thermal sensation during temperature ramps up to ±5 K/h.

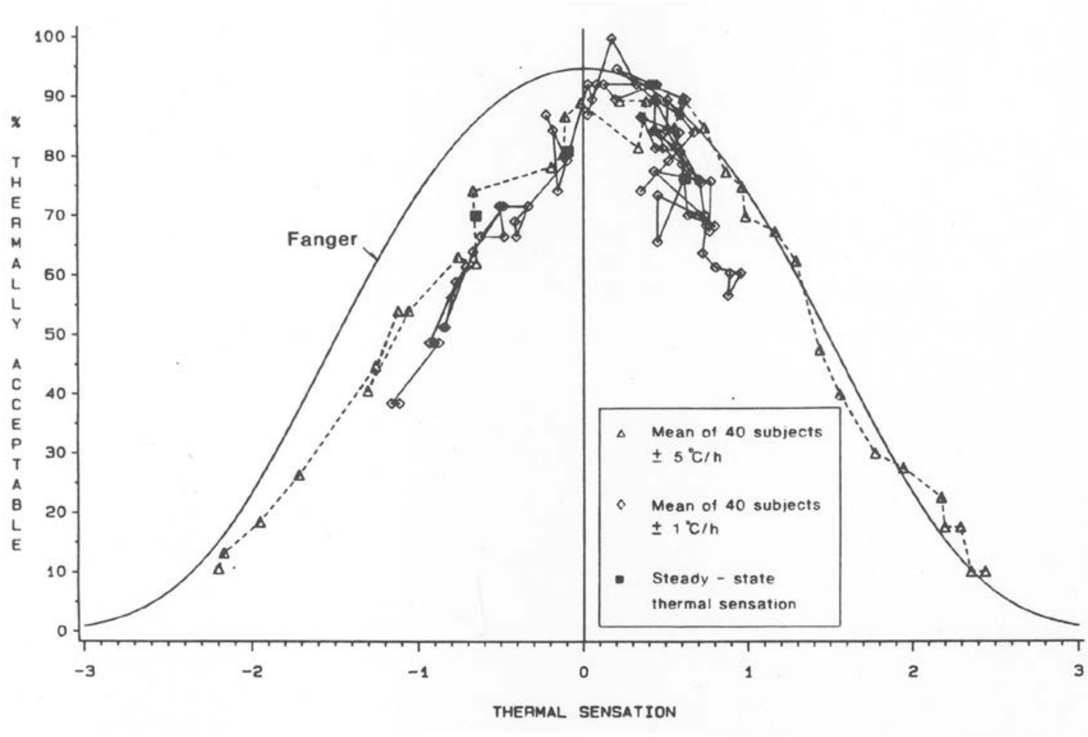

Figure 2: Observed thermal acceptability during exposure to temperature ramps as a function of mean thermal sensation compared with the PMV/PPD model (Knudsen et al. 1989)

Berglund and Gonzalez (1978b) also focused on the influence of different relative air humidity levels on the acceptability of temperature ramps lasting 8.5 hours. Human subjects wearing summer clothing were first exposed to an environment with a constant temperature of 25 °C and a dew point of 10 °C. Afterwards, the subjects were exposed to the temperature ramps of 0.6 K/h (23 °C to 27.8 °C) with dew points of 10 °C and 20 °C respectively. Subjects had a clothing insulation of 0.5 clo and performed office work. The results showed that a temperature ramp of 0.6 K/h between 23°C and 27°C was thermally acceptable to more than 80% of the subjects. Moreover, subjects preferred the low humidity temperature ramp to the environment with constant temperature.

Other studies reviewed in a paper by Hensen (1990) concluded that slow temperature changes up to ±0.5 K/h have no influence on the width of the comfort zone as established under steady-state conditions. A study by Hensel (1981) showed that the thermal sensation threshold (difference between neutral temperature and temperature when cold or warm sensations occur), decreased inversely with the rate of temperature change; the faster the ramp the smaller the difference between warm and cold sensations. The thermal sensation threshold is depended on the temperature prior to the onset of the ramp and on the direction of the change and on the exposed part of the body plus its area.

In the study by Kolarik et al. (2009) fifty-two experimental subjects (50% female) were seated in a climate chamber and exposed to operative temperature ramps with different slopes, directions and durations during two related experiments. The first experiment covered a temperature range of 22-26.8 ºC and subjects wore light clothing (approx. 0.5 clo). In this experiment, the operative temperature ramps of 0.6 K/h (lasting 8 hours), 1.2 K/h (4 hours), 2.4 K/h (2 hours) and 4.8 K/h (1 hour) were studied. In one session subjects were exposed to a constant temperature of 24.4 ºC for four hours. The second experiment covered a lower temperature range of 17.8-25 ºC, and subjects wore heavier clothing (approx. 0.7 clo).

Temperature ramps of 0.6 K/h (8 hours), 1.2 K/h (6 hours), -0.6 K/h (8 hours) and -1.2 K/h (6 hours) and exposure to a constant temperature of 21.4 ºC (6 hours) were examined.

The assessments of thermal sensation, acceptability of the thermal environment, perceived air quality and intensity of SBS symptoms were done by means of the online questionnaires. Subjects' performance was measured by simulated office work, including tasks such as addition, proof-reading, reading and comprehension and text typing. A linear relationship between mean thermal sensation and operative temperature was observed in all temperature ramps studied. Very moderate ramps of ±0.6 K/h were sensed by sedentary subjects with 3-4 hours delay (depending on the level of clothing). This indicated that even moderately changing operative temperature ramps were sensed by sedentary subjects when exposure times were long enough – in this case exceeded four hours. The authors concluded that the observed relationship between mean thermal sensation and the percentage of thermally dissatisfied subjects was in fairly good agreement with predictions by the PMV/PPD model (Figure 3).

No significant effect on SBS symptoms related to local irritation of mucous membranes was found, while intensity of headache, well feeling and concentration ability were significantly affected in most of the ramps. The study did not find any significantly consistent effect of individual temperature ramps on office work performance, but suggested that increasing operative temperature appeared to negatively affect the speed of addition and text typing, regardless of the slope of the ramp, when compared to a constant temperature condition.

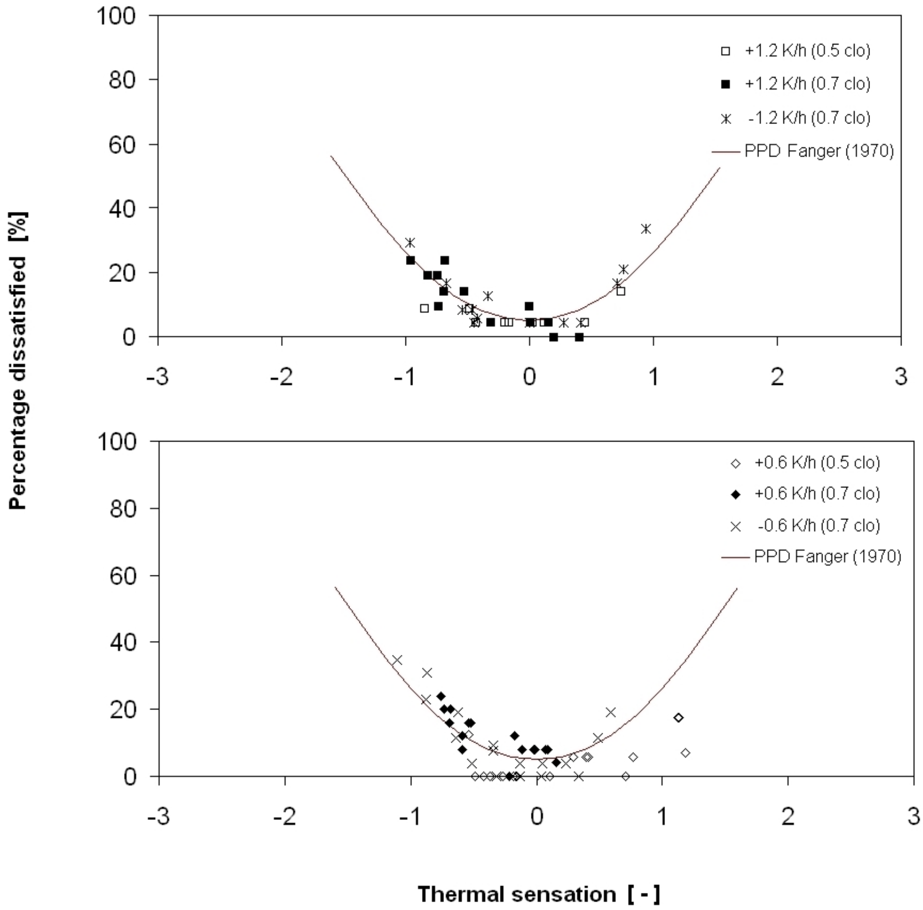

Figure 3: Percentage of subjects dissatisfied with the thermal environment as a function of mean thermal sensation in the experiments of Kolarik et al. (2009)

Schellen et al. (2010) compared the effects of a moderate temperature drift (+2 K/h for 4 hours followed by -2 K/h for 4 hours) on physiological responses, thermal comfort and productivity of young (22-25 years old) and elderly (67-73 years old) subjects. The results of the study showed that that the thermal sensation of the elderly subjects was, in general, 0.5 scale units lower in comparison to younger subjects.

According to Schellen et al. the thermal sensation of the elderly subject was related to air temperature only, while the thermal sensation of the younger adults was also related to skin temperature. When exposed to the constant temperature, the elderly preferred a higher temperature in comparison with the young adults. The researchers also concluded that the PMV/PPD model was able to predict the thermal sensation of young adults while it slightly overestimated the thermal sensation for elderly subjects. No negative influence of the temperature drifts on subjects' productivity (text typing and addition) was found.

A study by Toftum et al. (2010) focused on the thermal sensation and productivity of subjects exposed to increasing and decreasing dynamic temperature drifts while being allowed to adjust their clothing insulation as desired. The study addressed both the summer and winter comfort ranges of temperature, and subjects were exposed to rates of temperature change of -1.2 K/h, +1.2 K/h, and 2.4 K/h as well as to a constant temperature of 24.4 °C (summer) and 21.4 °C (winter). Exposure duration was four hours except for the 2.4 K/h condition when it was two hours.

Thermal sensation responses observed with adjustable clothing insulation did not differ from those observed with fixed clothing insulation as reported by Kolarik et al. (2009). The aggravation of general sick building syndrome (SBS) symptoms during longer exposures (>4 hrs) observed by Kolarik et al. (2009) with fixed clothing was not observed by Toftum et al. (2010). In addition, the study did not detect any systematic influence on performance of operative temperature ramps, regardless of the clothing adjustment opportunity.

5.5.3 Effect of thermal transients on productivity

In early research on thermal transients, cyclical temperature swings were studied in climate chambers to determine the influence of the temperature transients caused by HVAC control systems on human performance. Wyon et al. (1971) investigated the factors affecting subjective tolerance of temperature swings. The researchers concluded that subjects tolerated greater amplitudes when performing mental work than when resting.

In another study, Wyon et al. (1973) exposed subjects with clothing insulation of 0.6 clo to eight different temperature conditions including swings around the average preferred temperature. The following combinations of peak-to-peak amplitude and period were investigated: constant temperature, 2 and 4°C/8 min; 2, 6 and 8 °C/16 min; 4 and 8 °C/32 min. Each condition was maintained for three consecutive periods. Subjects were asked to evaluate their thermal discomfort. Their performance of an addition test was also measured.

After experiencing three complete periods, subjects were asked to assess their level of arousal, degree of fatigue and the freshness.

The researchers identified two types of effect of temperature swings on working subjects. Small, rapid swings around the preferred temperature resulted in a decreased work rate and decreased accuracy. Larger, slower temperature swings were associated with faster (although not significantly faster) rates of working and the accuracy seemed to tend towards that achieved at a constant temperature. It was concluded that large temperature swings may have a positive effect on performance, but they increase discomfort and should thus be self-imposed, while small rapid temperature swings are equivalent to a small increase in temperature.

Another study by Wyon et al. (1975) showed clearly that it was the resulting thermal state of the occupant, not the environmental temperature itself, which affected performance. The study showed that the performance of different kinds of mental work like addition test, word memory test etc., was relatively the same (the difference was less than 10 %) under the two test conditions of thermal comfort (clothing insulation levels of 0.6 clo and 1.5 clo). When subjects wore light clothing, their average comfort temperature was 23.2 °C, while with heavy clothing their average comfort temperature was 18.7 °C. The difference in the mean preferred air temperature between the conditions was approximately 4.5 K. No significant difference in performance at different levels of temperature and relative humidity (20 °C/40 % RH, 23 °C/50 % RH and 26 °C/60 % RH) was found by Fang et al. (2004) when subjects were able to adjust their clothing to maintain thermal comfort under all conditions.

In the field study conducted in a call centre by Tham et al. (2003) the effect of the air temperature as well as the effect of the air supply rate was investigated. The length of a call was used as a measurement of the performance. The results showed that lowering the temperature 2 K from 24.5 °C resulted in an increase in the performance by approximately 5% even though subjects were more thermally comfortable at the higher temperature.

In addition, a temperature intervention study carried out in a climatic chamber simulating office conditions found a significant negative effect of raising the room temperature set point by 4ºC (from 20-22ºC to 24-26ºC) on the performance of an addition task (Toftum et al. 2005).

Fang et al. (1998) showed that indoor air temperatures have a clear impact on perceived air quality. A significant increase of air freshness was perceived at decreased air temperature and humidity. A linear relation between the enthalpy of the air and acceptability of the air quality was found. Researchers also noticed that after about 30 minutes from the beginning of the exposure some adaptation, mainly to odour intensity, occurred.

5.5.4 Temperature ramps/drifts in current standards

The ASHRAE Standard 55 (AHSRAE 2010) describes temperature drifts and ramps as steady, monotonic and non-cyclic operative temperature changes. Drifts refer to passive, uncontrolled temperature changes and ramps to actively controlled temperature changes. The standard deals also with temporal temperature variations. Only temperature fluctuations, which are not under occupants' control, are addressed in this section. When it comes to temperature drifts *and ramps, requirements apply to the variations of temperature with a period greater than 15* minutes. Table 1 shows the recommended maximum rate of temperature change allowed during specific periods.

Time Period [h]	**0.25**	**0.5**	**1**	**2**	**4**
Maximum allowed change of the operative temperature [°C]	1.1	1.7	2.2	2.8	3.3

Table 1: Limits of operative temperature drifts and ramps (ASHRAE 2010)

According to the standard, allowed operative temperature changes should be applied so that limits for all defined periods are fulfilled. For example, the operative temperature may not change more than 2.2 K/h during a 1-hour period, but at the same time, it may not change more than 1.1 K/h during any 0.25-hour period within that 1-hour period.

The EN ISO Standard 7730 (ISO 2005) also deals with non-steady-state thermal environments. It describes three basic types of non-steady-state environment: temperature cycles, temperature drifts or ramps and temperature transients. For temperature drifts and ramps, the standard recommends using the steady-state evaluation method if the rate of temperature change is less than 2 K/h. The direction of the temperature change is not specified.

5.5.5 Discussion

As it can be seen from the reviewed literature, the conclusions from the studies concerning cyclic temperature swings indicate that larger and slower temperature swings can increase work rate. In addition, the accuracy of the conducted tasks can be compared to that achieved in an environment with a constant temperature. However, because an increase of thermal discomfort was observed, it was suggested that swings should be controlled by the occupants. The slowest temperature swing studied (4 K/32 min) still means a much faster temperature ramp, approx. 8 K/h, than the highest ramp studied by Knudsen et al. (1989) (5 K/h). Berglund and Gonzalez (1978a) compared obtained data of thermal acceptability to the 80% acceptability limits defined by ASHRAE Standard 55-1974. They concluded that the standard was conservative, especially at its upper temperature limit, when drifting temperatures were taken into account.

Results of the recent studies suggest that exposure to the temperature drifts does not primarily enlarge the thermal comfort range of the subjects (Kolarik et al. 2009). Toftum et al. (2010) conclude that their study generally verified the ASHRAE recommendations regarding drifting temperatures (ASHRAE 2010). The latter studies also answer the question of whether definition of the comfort zone by using PMV/PPD model is appropriate for environments with temperature drifts/ramps, earlier addressed by Knudsen et al. (1989). It seems that the percentage of subjects dissatisfied with the thermal environment follows the prediction by the PMV/PPD model for temperature drifts/ramps up to 4 K/h.

The recent climate chamber studies also relate exposure to the moderate temperature transients to human performance and perception of health related symptoms. Their results indicate that long lasting temperature up-ramps will be realized by the occupants and higher resulting temperatures, close to the upper limit of the comfort zone (24 - 26 °C) can lead to decrease of office work performance. Moreover, the recent studies stress the importance of the opportunity for behavioural adaptation (Toftum et al. 2010) as well as necessity to consider individual differences, namely age, among the building occupants (Schellen et al. 2010).

5.5.6 Conclusion

As can be seen from the presented literature review, theoretical knowledge concerning the effect of temperature transients on human thermal comfort was recently expanded with data on the effect of moderate temperature drifts or ramps on human health and productivity. The recently conducted studies provide experimental evidence that even drifts/ramps with very moderate operative temperature changes (about 0.5 K/h) are perceived by sedentary or slightly active persons in an environment with low air movement, though with a certain delay. These issues of office work performance and health related symptoms were addressed both in studies comprising short, cyclical temperature swings around the preferred ambient temperature of steady-state thermal environments and in studies focused on moderate temperature drifts. Although these effects were more pronounced with the first type of studies, the effect of long lasting moderate drifts should not be disregarded.

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5.6 Thermal sensation, intensity of health related symptoms and office work performance of occupants with possibility of behavioural modification of clothing under exposure to moderate operative temperature ramps

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5.6.1 Introduction

In developed countries, buildings account for up to 30 - 40 % of the energy consumption, and an important challenge to HVAC engineers is thus to develop new climatic systems or indoor climate control strategies that may reduce this current high energy demand (EC 2006). One feasible means of reducing the energy consumption is utilization of a building's thermal mass in combination with night cooling or heating, or cooling by pipes embedded in floors, walls or ceilings (slab heating or cooling). Compared with traditional HVAC systems, the energy consumption of the new systems may be considerably lower (Hauser et al. 2005). However, the trade-off may be less strict temperature control resulting in temperatures that drift somewhat during the day rather than a steady indoor temperature, which is a common goal in most climate controlled buildings.

In buildings, in practice, occupants who feel too warm or too cool will take active steps to counteract thermal discomfort, e.g. adjust a thermostat, if possible, or their clothing insulation, although dress code in some buildings may prevent this form of adjustment. Additional means to reduce warm exposure include occupant controlled opening of windows or use of local desk fans. Occupant behaviour may have a profound effect on the energy consumption in a building, and indeed Andersen et al. (2007) have shown that occupant behaviour can influence the energy consumption by as much as 330 % on comparing a rational and a non-rationally behaving occupant who for instance chooses to open a window rather than adjusting a radiator thermostat to lower the temperature. Including occupant behaviour in building operation may justify relaxed temperature criteria, but may also require training of the occupants to benefit from the potential concurrent reduced energy consumption.

The current version of ASHRAE Standard 55 "Thermal environmental conditions for human occupancy" addresses both temperature drifts and ramps and characterizes drifts as passive, uncontrolled temperature changes (ASHRAE 2010). The standard specifies maximum recommended rates of temperature change during periods of time ranging from 15 min to 4 hrs. For example, the standard recommends that the operative temperature should not change more than 2.2 K/h during a 1-hour period, but at the same time, it should not change more than 1.1 K/h during any 0.25-hour period within that 1-hour period. However, the current basis for evaluating effects of drifting temperatures on building occupants is based mostly on engineering judgment and to some extent on earlier thermal comfort research. Additional knowledge is needed that describes how other important factors as the intensity of symptoms, e.g. headache or irritated eyes, perception of air quality and occupant performance are affected by the daily variation of temperature that may occur with new types of climatic systems.

This section presents results of climate chamber experiments in which subjects were exposed to temperature drifts while being allowed to adjust their clothing insulation as desired. In an earlier paper, results of experiments carried out with subjects' clothing insulation maintained constant were reported (Kolarik et al. 2009). The objective of the study was to substantiate the scientific basis of the recommendations on drifting temperatures as stated in ASHRAE (2010) and to extend the scope of the recommendations to cover not only thermal comfort, but also health and performance.

5.6.2 Methods

Twenty-five healthy subjects (10 female and 15 male) participated as volunteers. During the experiments, six subjects at a time were exposed at separate workstations consisting of a desk, a chair and a PC connected to a local intranet. Subjects were exposed to both increasing and decreasing temperature ramps while being allowed to modify their clothing insulation as desired.

Experimental conditions

Season	**Rate of temperature change (°C/h)**	**Duration of the exposure (h)**	**Beginning of temperature ramp (°C)**	**End of temperature ramp (°C)**
Summer	+1.2	4	22.0	26.8
Summer	+2.4	2	22.0	26.8
Summer	0.0	4	24.4	24.4
Winter	+1.2	4	19.0	23.8
Winter	-1.2	4	23.8	19.0
Winter	0.0	4	21.4	21.4

Table 1 : Experimental conditions of the study

The experimental conditions were divided into two temperature ranges simulating summer and winter conditions. Decreasing temperature ramps were applied only under winter conditions. With increasing temperatures, ramps began near the lower limit of the temperature comfort range and ended near the upper limit. Table 1 summarizes the experimental exposures. Absolute humidity was kept constant under all conditions, resulting in a variation of the relative humidity with varying temperature. The airflow rate was constant at 173 L/s corresponding to 28.8 L/s per person.

Prior to the beginning of a temperature ramp or exposure to a constant temperature, subjects were acclimatized during 30 min at 21.4 °C corresponding to winter conditions or 24.4 °C corresponding to summer conditions. In addition, a reference exposure to constant temperature of 21.4 °C and 24.4 °C was included in the experimental design.

Measurements

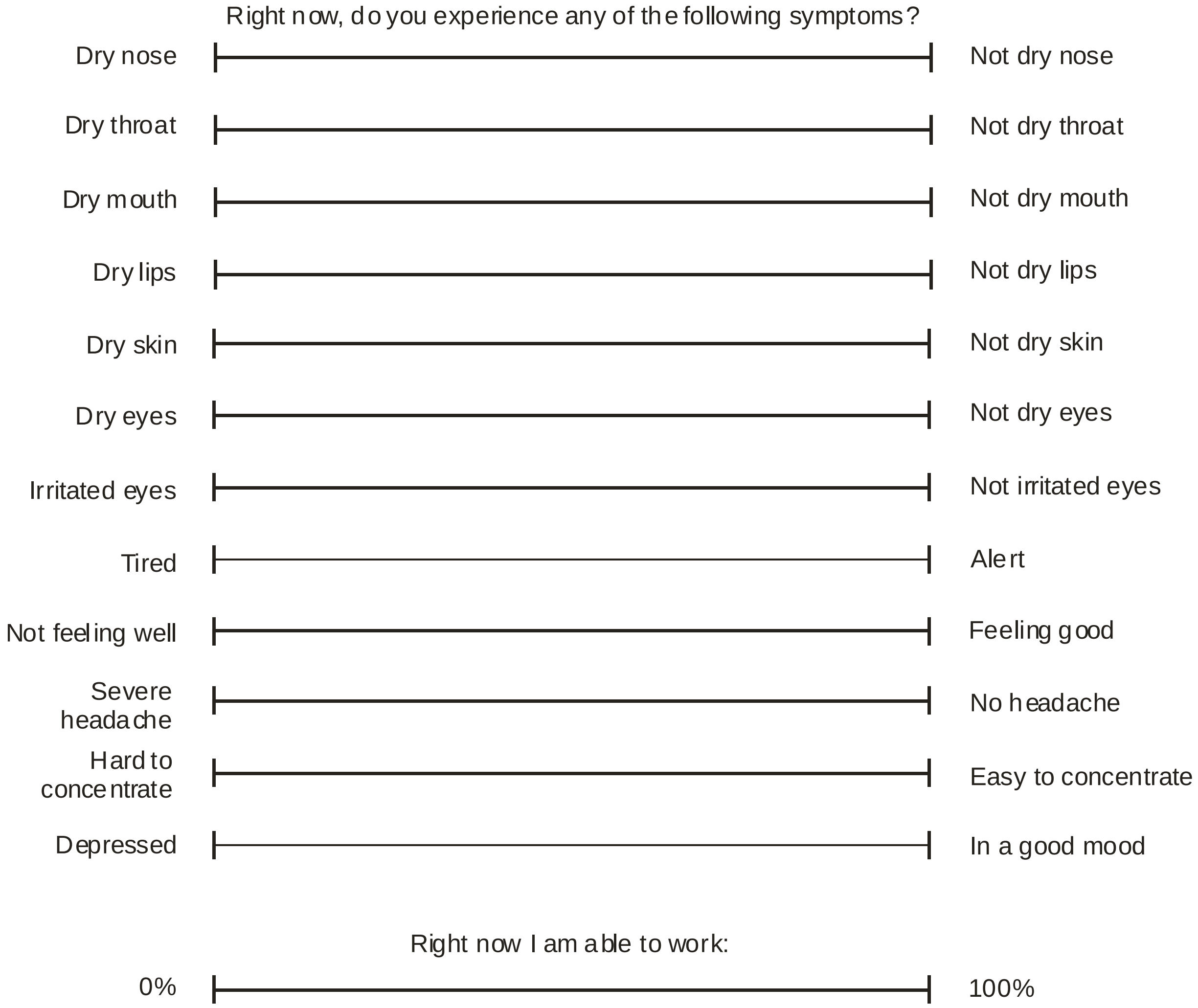

Figure 1: Visual Analogue Scales presented to the subjects two times an hour during the experiments

Air and operative temperatures, air velocity, and air humidity were measured at 1 min intervals at the centre of the chamber 0.6 m above the floor.

The Remote Performance Measurement (RPM) approach was used to administer and schedule questionnaires and performance tasks via an intranet during the experiments (Toftum et al. 2005). The questionnaire included a 7-point thermal sensation interval scale, scales to assess the acceptability of temperature and air quality and a 6-point interval scale to assess odour intensity. Visual Analogue Scales (VAS) were used to assess perceptions and the intensity of selected specific and general Sick Building Syndrome (SBS) symptoms. In addition, a scale to assess self-estimated performance was included. Figure 1 shows the VAS scales that were presented to the subjects at regular intervals during the experiments.

At the beginning of each session, subjects recorded the clothing items they wore. During the session subjects could adjust their clothing as desired and the adjustment was recorded via RPM to keep track of which item was changed when.

Four different types of simulated office tasks were used to measure subjects' performance: addition, proof-reading, reading and comprehension, and text-typing. Task outcomes were speed and errors, e.g. in the addition task, number of correct additions per minute or number of errors out of the total number of additions made (accuracy).

5.6.3 Results and discussion

Figures 2 and 3 show the progression of the mean thermal sensation votes and the corresponding recorded mean clothing insulation under summer and winter conditions. Even under constant temperature conditions (0.0 K/h) and during the entire experimental period, subjects seemed to find it necessary to increase their clothing insulation to avoid feeling cool. However, subjects rather infrequently modified their clothing insulation although the opportunity was available to them. Altogether, subjects were not able to compensate completely for the dynamic temperature changes, even though they were allowed to modify their clothing insulation.

A smaller effect of temperature on thermal sensation and comfort was expected in the current experiments when compared with earlier experiments by Kolarik et al. (2009) in which the environmental exposures were the same, but subjects not allowed to modify their clothing insulation. However, a statistical comparison of the data from the present study to the data by Kolarik et al. (2009) showed that even though subjects could modify their clothing insulation, this behavioural adjustment had not resulted in different perception of the given thermal environment.

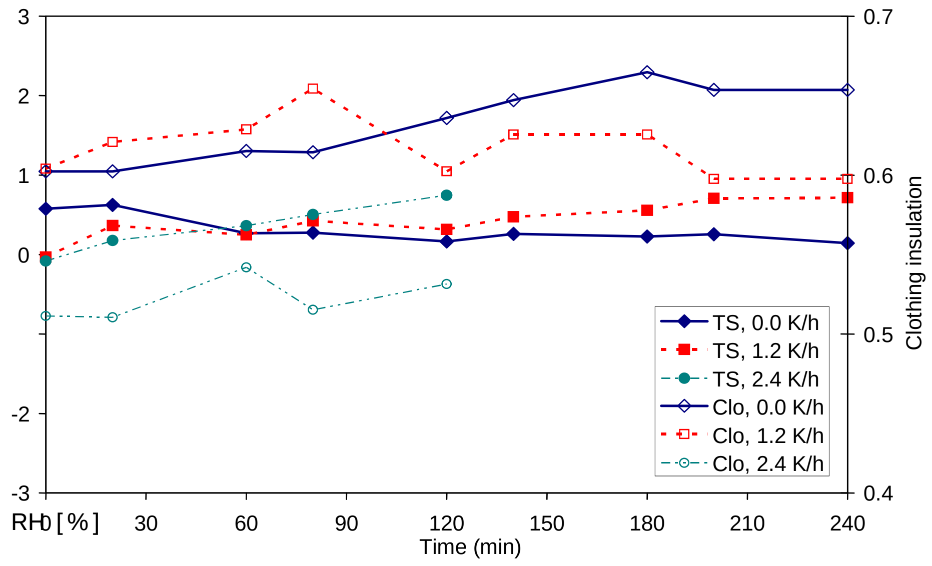

Figure 2: Mean thermal sensation votes and the corresponding mean clothing insulation under summer conditions as a function of time

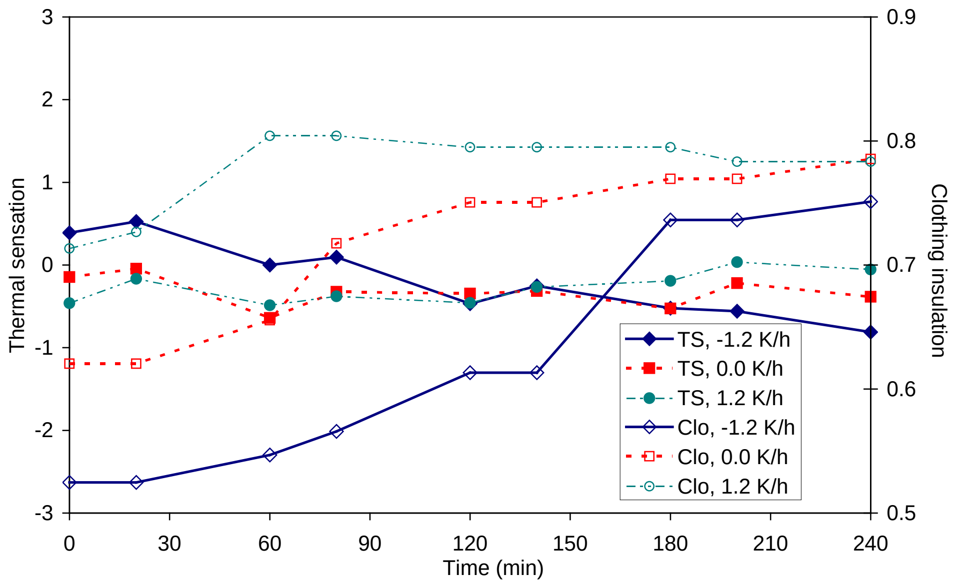

Figure 3: Mean thermal sensation votes and the corresponding mean clothing insulation under winter conditions as a function of time

Figure 4 shows mean thermal sensation votes as a function of temperature as observed in the present study and in the study by Kolarik et al. (2009) at a rate of temperature change of 2.4 K/h. The figure shows that there was a clear influence on thermal sensation of the temperature change, and the regression lines closely coincide. Only at 1.2 K/h under winter conditions, the relation between temperature and thermal sensation differed between the two mentioned studies.

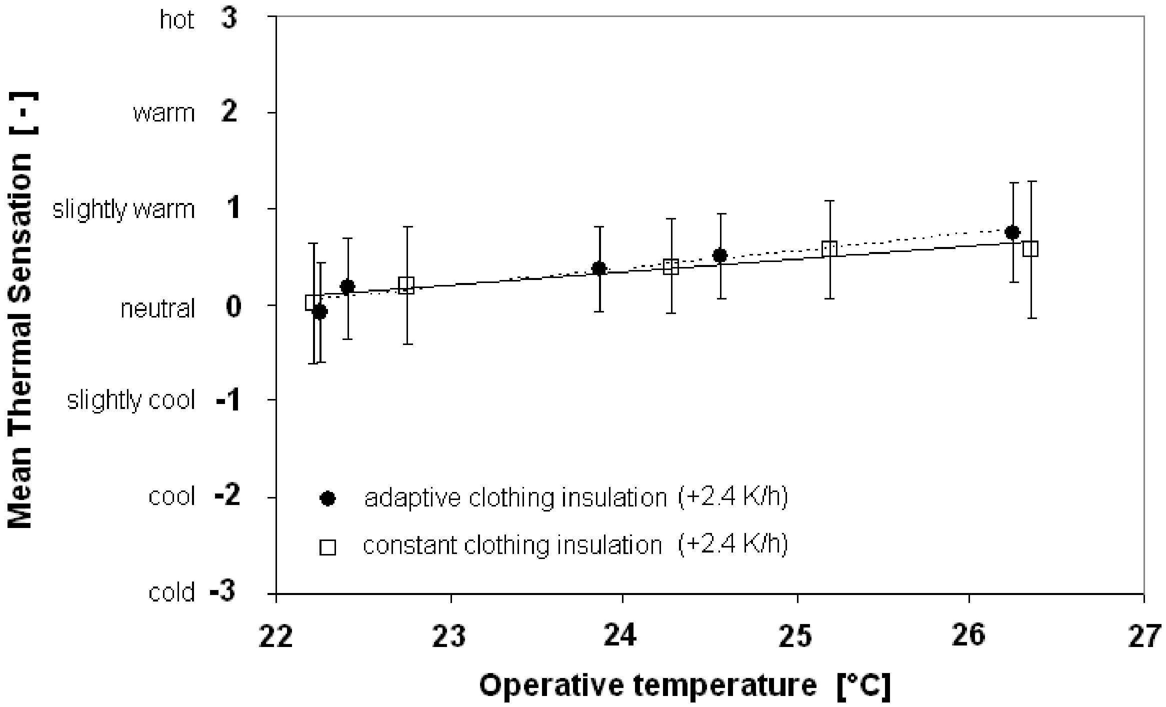

Figure 4: Mean thermal sensation as a function of temperature as observed in the present study and in the study by Kolarik et al. (2009) at a rate of temperature change of 2.4 K/h

Figure 5 shows comfort ranges corresponding to 20% of subjects dissatisfied with the thermal environment as determined for the present study as well as for the study with the fixed clothing insulation (Kolarik et al. 2009). The figure also indicates the corresponding comfort range determined with the ASHRAE Thermal Comfort Tool (Fountain and Huizenga, 1996) for average clothing insulation as determined in the summer and winter experiments. Only little effect of the clothing modification opportunity was seen and it did not result in a wider comfortable temperature range. As seen from the figure, the average clothing insulation differed only modestly between seasons, which may be the reason that the summer and winter comfort temperature ranges were rather similar. In general, subjects under all exposures accepted lower temperatures than predicted by the ASHRAE Thermal Comfort Tool.

The intensity of SBS symptoms was generally low and varied only little between experimental conditions. With subjects who were not allowed to modify their clothing insulation, Kolarik et al. (2009) found that general symptoms were more affected by temperature ramps than were specific symptoms related to local irritation of the mucous membranes (nose, eyes, mouth) and that increasing temperature ramps increased significantly the intensity of headache, reduced the ability to concentrate and decreased self-evaluated performance, and vice-versa for decreasing temperature ramps. For the general symptoms as observed in the present study, only the intensity of headache increased significantly ($p=0.045$) during one experimental condition (+1.2 K/h winter). The intensity of no other symptom changed progressively during the experiments, indicating that permitting subjects to modify their clothing insulation resulted in insignificant changes of the intensity of the general symptoms for the duration of the experiments.

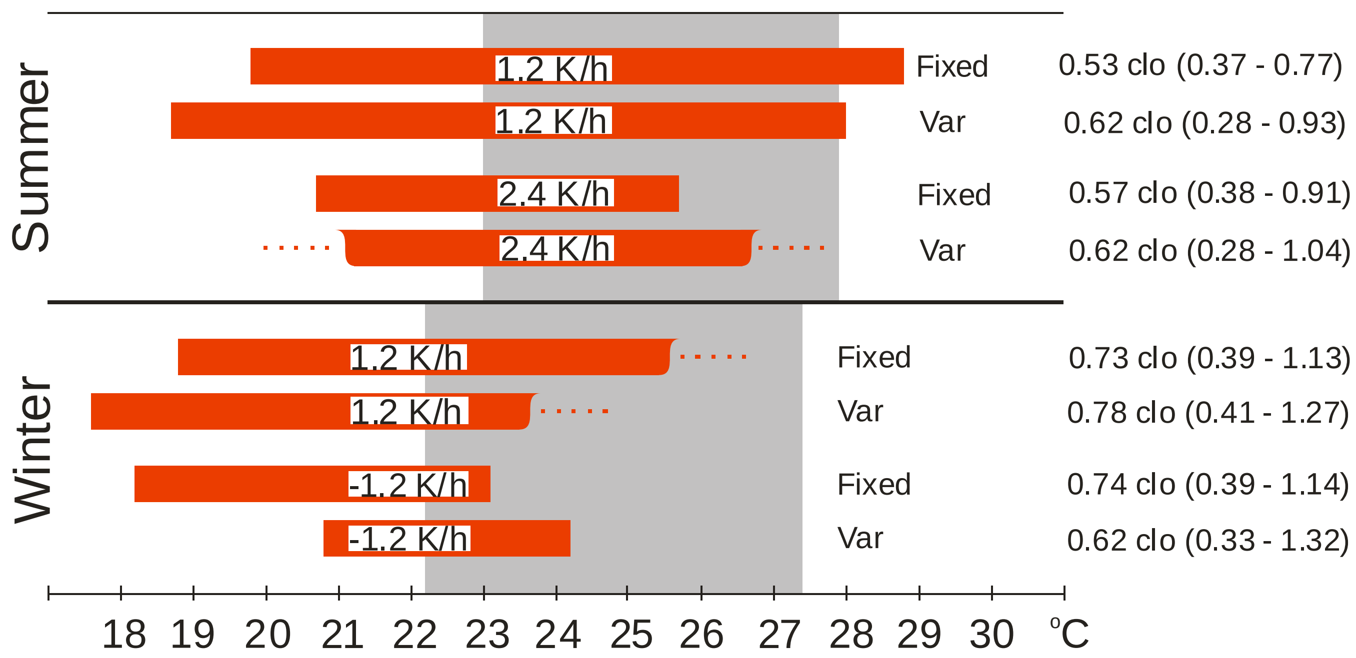

Figure 5: Comfort ranges corresponding to 20% dissatisfied as determined for experiments with fixed and variable clothing insulation (horizontal bars continued with a dotted arrow indicate that the results did not allow determination of a limit to the comfort range; the grey area corresponds to the comfort range determined with the ASHRAE Thermal Comfort Tool for average clothing insulation as determined in the summer and winter experiments)

Self-assessed performance varied significantly between experimental conditions, but did not change during the course of experiments as a result of the exposure. Task performance was compared between the one condition with constant temperature and the other conditions with drifting temperatures. During summer exposure the comparison was made between experiments with 0 K/h and 1.2 K/h temperature drifts in which each test type was presented to the subjects twice. It complicated the analysis that with the current experimental design, temperature and time were confounded, i.e. potential effects of the drifting temperature could not be separated from the effect of exposure duration, which may affect the performance outcome by the influence of learning and exhaustion. However, by comparing performance metrics between constant and drifting temperature conditions and doing so after identical exposure durations, the effect of exhaustion/learning could be minimized. Altogether, the experiments showed no clear effect of drifting temperature on performance, during neither winter nor summer exposures.

5.6.4 Conclusions

Allowing subjects to modify their clothing insulation while being exposed to temperature drifts resulted in only negligibly different thermal sensation and acceptability than with fixed clothing insulation. In contrast to experiments carried out with fixed clothing insulation, increasing temperatures did not aggravate general SBS symptoms or decrease self-assessed performance. No consistent effect of temperature drifts on the performance of office work was observed.

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5.7 Differences between young adults and elderly in thermal comfort, productivity and thermal physiology in response to a moderate temperature drift and a steady-state condition

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5.7.1 Introduction

Both thermal comfort and energy-use play an important role in the performance of a building. Approximately one-third of the primary energy used in developed countries is consumed by heating, ventilating and air conditioning in residential, commercial and public buildings (IEA, 2007). Given these energy requirements, it is relevant to study how energy-savings can be achieved together with acceptable thermal comfort and performance.

Results from naturally ventilated buildings in practice revealed that satisfaction with the thermal environment does not mean that this environment has to be controlled at a constant indoor air temperature (de Dear and Brager, 1998). Compared to a constant temperature, allowing the temperature to drift could be a means to reduce energy-use.

Literature review of temperature drift effect on thermal comfort and performance

The overview in this sub-item complements the more comprehensive review presented in section 5.5. by Koralik et al. on moderately drifting operative temperatures.

In the past, several studies have been conducted to examine the influence of a temperature drift and a wider temperature range on thermal comfort and performance. These studies show that temperature drifts can be acceptable in air-conditioned buildings without self-control. The results of these studies show that slow temperature ramps up to 0.5 K/h have no effect on the width of the comfort zone as established under steady-state conditions; the environment is experienced as in steady-state conditions, i.e. slow temperature ramps (0.5K/h) were not significantly noticeable to the occupants (Griffiths and Mc Intyre, 1974; Berglund and Gonzalez, 1978a and 1978b; Rohles et al., 1985). Berglund and Gonzalez also stated that at fast temperature changes (1.0K/h and 1.5K/h) the allowable deviation from the optimum thermal condition was larger in comparison to slow temperature changes (0.5K/h).

Hensen et al. (1990) and Kolarik et al. (2005) concluded from their reviews that for rates between 0.5K/h and 1.5 K/h there is no clear evidence of increased or decreased comfort zones due to temperature drifts, except from experiments with uncommon acceptability assessment procedures. From these studies it can be concluded that the knowledge regarding the effects of temperature drifts on human thermal comfort is still limited.

In a recent laboratory study by Kolarik et al. (2007) different operative temperature ramps (±0.6 K/h, ±1.2 K/h, +2.4 K/h, +4.8 K/h; temperature ranges: 22-26.8°C and 17.8-25°C) were investigated to determine the influence of the slope. They found that a slow temperature drift (±0.6 K/h) was perceived by the subjects with 3-4 hours delay (depending on clothing level). During the first 3-4 hours of exposure subjects did not distinguish a slow temperature increase (+0.6K/h) from a constant temperature level (21.4°C and 24.4°C). These results are in agreement with earlier mentioned studies by Berglund and Gonzalez (1978a and 1978b) and Rohles et al. (1985).

The results also indicate that not the temperature ramp, but the combination of a temperature level above 24.4°C and the time of exposure affected the thermal sensation. Furthermore, a linear relation was found between mean thermal sensation and operative/air temperature for all the studied ramps.

In the building design phase it is useful to predict thermal comfort of the occupants; often the PMV/PPD model is used for this. However, Nicol and Humphreys (2002) showed, based on data of the ASHRAE RP-884 database (de Dear et al., 1997), that the PMV model might not be applicable to predict thermal comfort for conditions that deviate much from thermal neutral conditions.

Although the PMV model was developed for steady-state conditions, the study by Kolarik et al. (2007) indicates that the PMV model might also be applicable for transient conditions. For all slopes the relation between instantaneous mean thermal sensation and prediction by the PMV model (ISO 7730, 2005) was in reasonably good agreement (Kolarik et al., 2007). This was found by Schellen et al. (2008) as well. The same was noted by Knudsen et al. (1985); they concluded that the PMV model could possibly be used for temperature ramps up to ±5 K/h.

Seppänen and Fisk (2005) describe a literature review on the influence of temperature on performance. Several types of office tasks were analyzed, including text typing and the duration of telephone calls during call centre work. According to their analyses, room temperature had no influence between 20ºC and 25ºC. Above 25ºC, and below 20ºC, a decrease of 2%/ºC in performance was observed. These findings were confirmed in studies by Seppänen and Fisk (2005) and Tanabe (2006).

On the contrary, Toftum (2005) discovered a significant negative effect on performance when increasing the temperature from 20-22ºC to 22-24ºC.

Studies concerning the effects of temperature drifts on performance and productivity were only found for short cyclical temperature swings around the preferred ambient temperature. Kolarik et al. (2005) concluded that small rapid swings (4K/8min) around the preferred temperature resulted in a decreased performance and work speed. Conversely, larger and slower swings (4K/32min) were related to a higher work speed in comparison to results achieved under steady-state conditions. The performance was equal to the performance achieved under steady-state conditions. According to these findings, temperature transients can have a positive influence on the work speed (productivity) and perhaps performance, although thermal discomfort cannot be ruled out.

Ageing, thermal comfort and productivity during moderate temperature drifts

For both temperature and productivity no studies are available to determine the effects of ageing on thermal comfort and productivity during a moderate temperature drift. In this study this effect has been investigated.

The studies mentioned above reveal a challenge to explore whether faster (>±0.5K/h) temperature drifts, both increasing and decreasing, are acceptable during a longer period of time in air-conditioned buildings. Moreover, there exists a need to study thermal preferences of elderly and resulting requirements (van Hoof and Hensen, 2006; van Hoof, 2008).

ASHRAE (2009) states, based on research by among others Rohles and Johnson (1972), Fanger and Langkilde (1975) and Fanger (1982), that the thermal conditions preferred by elderly do not differ from those preferred by younger adults. This does not mean that the elderly and young adults are equally sensitive to cold or heat.

On the contrary, several studies indicate that the thermally neutral temperature and optimum thermal condition of elderly differ from the thermally neutral temperature and optimum condition of young adults, mainly because of an on average lower activity level (which implies a lower metabolic heat production). Therefore, elderly might require a higher ambient temperature to achieve thermal comfort in comparison to younger adults at equal clothing levels (Hardy and DuBois, 1940; Collins et al., 1981; Cena et al., 1986; Natsume et al., 1992; Havenith, G., 2001; Hashiguchi et al., 2004; van Hoof and Hensen, 2006; DeGroot and Kenny, 2007).

Because, in the western world the number of people aged 60 or older will increase from 15.4% in 1996 to 25.3% in 2030 (Howden-Chapman et al., 1999), it is relevant to study possible differences in thermal comfort, physiological responses and performance between young and elderly people experiencing a moderate temperature drift.

Following the above, the objective of this work was to study differences in thermal comfort, physiological responses and productivity between young and elderly people under a moderate temperature drift.

5.7.2 Methods

Design

The experiments were carried out in a climate room (4.5x3.7x2.3 m^3, LxWxH) at the laboratory of the unit Building Physics and Systems at Eindhoven University of Technology (Schellen et al., 2010, Figure 1).

Figure 1: Impression of test subjects in climate room

Sixteen subjects (8 young adults, aged 22-25 and 8 older adults, aged 67-73) were recruited to participate in the experiment. All subjects were male, healthy, normotensive and not taking any medications that might alter the cardiovascular or thermoregulatory responses to the temperature changes; subject characteristics per group are listed in Table 1.

	Age [yr]	**Height [m]**	**Weight [kg]**	**Body Fat [%]**
Young adults	22-25	1.83±0.11	82.7±8.6	14.5±3.3
Older adults	67-73	1.76±0.06	77.8±7.2	18.7±5.3
* Mean ± SD				

Table 1: Subject characteristics per age group

The subjects visited the climate room on two occasions (S1 and S2) that differed in indoor climate conditions. The order of the conditions was alternated (e.g. subject 1 started with S1 and ended with S2, subject 2 started with S2 and ended with S1, subject 3 started with S1, etc.).

S1: A steady temperature (21.5°C)

Session *S1* (duration 8h) was the control situation and the results of this session were used to assess possible time effects. The temperature was fixed at 21.5ºC (21.5±0.12ºC), which corresponds to a neutral thermal sensation (PMV≈0).

S2: A transient condition

During session *S2* a moderate temperature ramp (duration: 8h; temperature range: 17-25°C; temperature drift: first 4h: +2K/h, last 4h: -2K/h) was imposed. Through this course, both the effects of an increasing and decreasing ramp could be evaluated.

Most of the experiments done in the past focused on the effect of temperatures warmer than neutral. In this study temperatures colder than neutral were studied as well. The minimum temperature of 17°C was set to avoid shivering, and therefore it is assumed that the condition would not be unacceptably cold (Parsons, 2003). The maximum temperature of 25°C fits within the comfort zone (PMV<0.5) according to ASHRAE (2004) and ISO 7730 (2005). The imposed drift of 2K/h is within the comfort limit (ISO 7730, 2005).

Furthermore, this drift represents a building warming up during the beginning of the day, and cooling down during the second part of the day when the heating is turned off. It was assumed that the lower temperature in the second part of the day could perhaps positively influence the productivity due to 'freshness of mind'.

The applied temperature course is represented in Figure 2. Mean deviation from the desired temperature course was 0.08±0.49ºC.

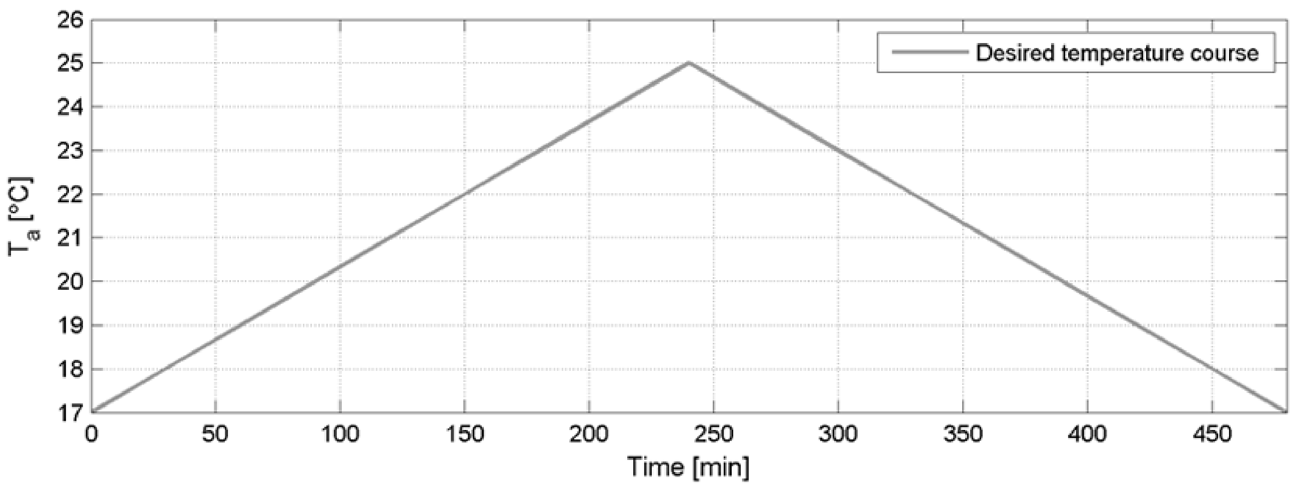

Figure 2: Designed temperature course condition S2

Prior to the measurements, the subjects performed a light exercise until skin vasodilatation occurred. This ensured that all subjects entered the climate room in an equal thermal state. After entering the climate room the experiment started with an acclimatization period (30 minutes). During this period, skin temperature sensors were attached and subjects' characteristics (height, weight and fat percentage) were determined. Subjects also received instructions regarding the use of the questionnaires. During the experiments the subjects wore standardized clothing, consisting of a cardigan, jogging pants, thin T-shirt, underpants, socks and shoes. The total heat resistance of the clothing ensemble, including desk chair, was approximately 1.0 clo.

The subjects continuously performed office tasks; their metabolic rate was estimated to be approximately 1.2 met (ISO 7730, 2005).

The volunteers were given detailed information regarding the purpose and the methods used in the study, before written consent was obtained.

Measurements

Twice per hour test subjects filled in a questionnaire which included a continuous 7-point thermal sensation interval scale (ISO 7730, 2005), scales to assess the acceptability of the thermal environment and Visual Analogue Scales (VAS) to assess adverse perceptions and the perceived indoor environment (Kildesø et al., 1999). A questionnaire to assess self-estimated performance and a questionnaire to assess perceived stress were included as well. To assess the performance, a 'Remote Performance Measurement' (RPM) method was used (Toftum et al., 2005). Within this method the performance was estimated by two simulated office tasks: text typing and addition. Both questionnaires and office tasks were presented in Dutch to the subjects through an Internet browser.

The differences in physiological responses, subjective responses and performance were statistically investigated using analysis of variance (ANOVA) and a linear mixed effects model (LME) treating each subject as a random factor. The experimental conditions were analyzed separately in the ANOVA model. To assess explaining variables for the thermal sensation and thermal comfort of the subject, stepwise linear regression was used. Significant effects are reported for $p<0.05$. Two statistical software packages were used to analyze the data: for the LME analyses the freely available R 2.9.2 (R Foundation for Statistical Computing, Vienna, Austria) software package was used; for all other analyses the commercially available software package SPSS 16.0 (SPSS Inc., Chicago, USA) was employed.

5.7.3 Results

Physiological measurements

Mean, distal and proximal skin temperatures and core temperature of young (Y) and elderly (E) subjects for both sessions (S1 and S2) are given in Figure 3.

For all three skin temperatures the difference between young and elderly was significant ($p<0.01$). The majority of the local skin temperatures (forehead, neck, scapula, upper chest, upper arm, hand, abdomen, paravertebral, shin, calf and instep) of the elderly were significantly lower than the skin temperature of the young adults. The temperature of the fingertip showed the largest difference, 29.1±1.90ºC [S1] and 27.5±2.76ºC [S2] for the young adults versus 24.8±2.73ºC [S1] and 24.9±2.12ºC [S2] for the elderly. However three measurement locations showed a deviation. At the underarm the difference was not significant, at the front and back of the upper leg (anterior and posterior thigh) the skin temperature of the elderly was significantly ($p<0.001$) higher than of the young adults, although this difference was relatively small (<0.8ºC).

The mean core temperatures of the elderly (36.6±0.27ºC [S1] and 36.5±0.33ºC [S2]) were significantly lower compared to their younger counterparts: 37.0±0.08ºC [S1] and 36.9±0.09ºC [S2]). Possibly this difference was caused by the difference in measuring technique for Tcore between the groups.

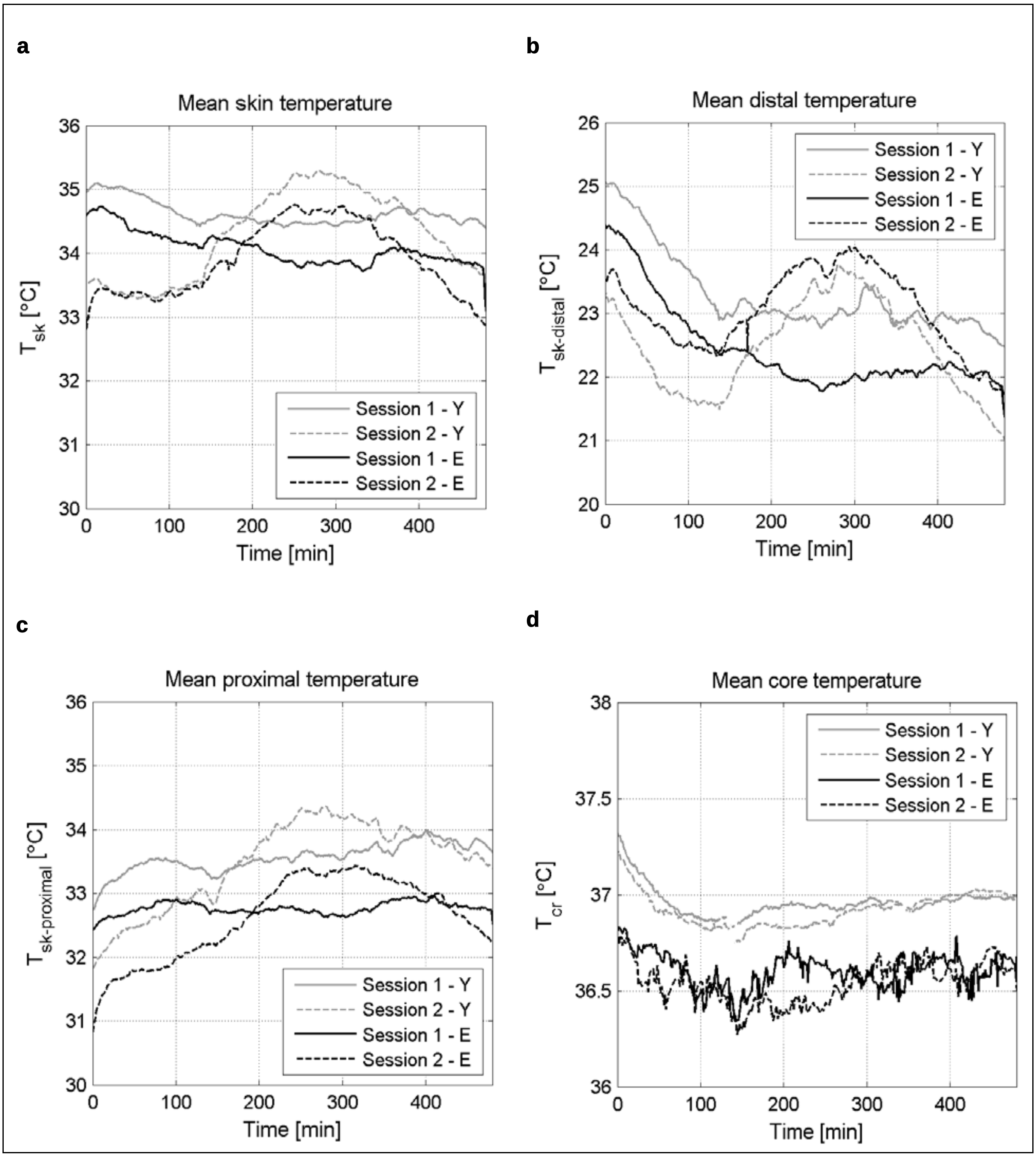

Figure 3. Mean (a), distal (b) and proximal (c) skin temperatures and core temperature (d) of young and elderly subjects during both experimental conditions

The difference (gradient) between fingertip and forearm temperature is given in Figure 4. Positive values indicate vasoconstriction (forearm temperature is higher than fingertip temperature), while negative values indicate vasodilatation. The fingertip–underarm gradient of the young adults was smaller during both sessions in comparison to the elderly. This is caused by the differences in vasoconstriction. Furthermore, the results of the young adults show a slightly negative difference (vasodilatation) as result of the high temperatures during session 2, in contrast to the elderly who maintained finger skin vasoconstriction.

The drop in distal skin temperatures during the first 100 minutes (both conditions, S1 and S2) is most probably the result of having the subjects start the experiment in vasodilatation state ($\Delta T_{(forearm\text{-}fingertip)} \approx 0$). This state was maintained during the acclimatization period due to the slightly elevated activity level. After the start of the experiment (t=0), the subjects were completely sedentary, which resulted in a slight decrease of core temperature (figure 3d) caused by a lowered internal heat production (metabolism). To maintain core temperature, constant vasoconstriction was activated, indicated by the increase of forearm-fingertip gradient (Figure 4) and drop in distal temperatures (Figure 3b).

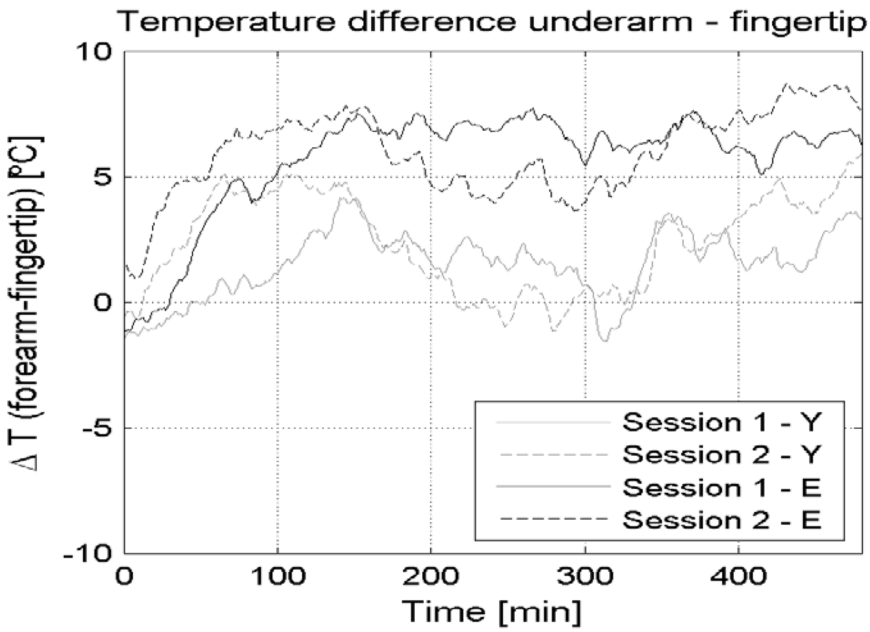

Figure 4: Mean difference between forearm and fingertip temperature of young and elderly subjects during both experimental conditions

Subjective responses

The results of the questionnaires were analyzed separately for both experimental conditions (S1 and S2) and for both parts of the condition (1: first 4 hours, 2: last 4 hours), to be able to distinguish between a constant temperature and a temperature drift and to analyze time effects.

Thermal sensation (TS) of the young adults was significantly (ANOVA, $p<0.001$) affected by the two different conditions (Figure 5a). In the design of the experiment the temperature of session S1 was determined to be equal to a neutral thermal sensation according the PMV model (ISO 7730, 2005). Averaged TS for the young subjects was -0.18±0.56 during session S1 and -0.52±0.76 during session S2. TS of the elderly was -0.67±0.66 and -0.63±0.93 respectively. TS during session S2 is not influenced by time.

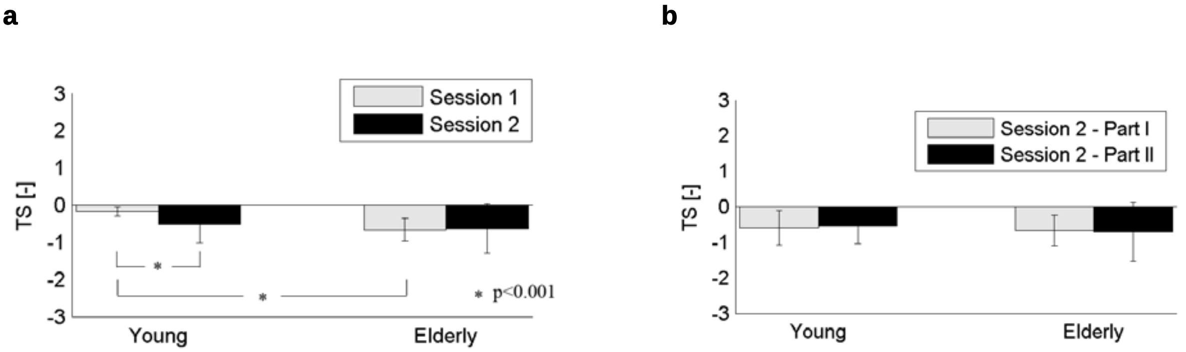

Figure 5: (a) Mean thermal sensation (TS) ± SD per measurement session (-3: Cold, -2: Cool, -1: Slightly Cool, 0: Neutral, 1: Slightly Warm, 2: Warm, 3 Hot) (b) Mean thermal sensation; Part 1: first 4 hours of session 2; Part 2: last 4 hours of session 2

Linear regression analyses, with TS as dependent variable and air temperature (T_a) as independent variable, show the difference in TS between the young and older adults. Generally, TS of the older adults is approximately 0.5 lower than TS of the younger adults (Figure 6). However, only for session S1, the differences are significant (LMM, $p<0.05$). Comparing the subjective votes for TS and predicted votes according the PMV model, a similar trend was detected; the general trend was in good agreement with the subjective votes. For the elderly, however, measured TS were 0.5 lower in comparison to PMV.

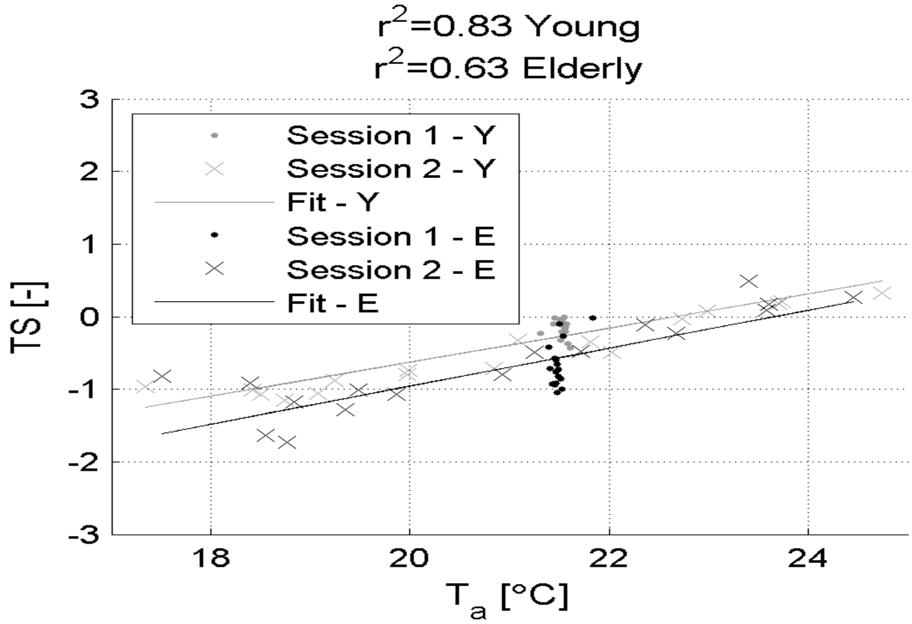

Figure 6: Linear regression analyses with TS as dependent variable and T_a as independent variable, for both sessions

The difference between young and elderly in thermal comfort (TC) was significant (LME, $p<0.001$). The elderly felt less comfortable during both sessions than the young adults, which was in agreement with TS. Since no significant differences were detected between the parts of the session, time effects were excluded for TC as well.

With respect to the preferred temperature, a significant difference (LME, $p<0.01$) was found for S1 (constant temperature); the elderly preferred a warmer setting, while the young adults requested no change in temperature. For both young and elderly subjects, mainly skin temperature (mean skin temperature, distal and proximal skin temperature, extent of vasomotion) had a significant ($p<0.05$) effect on TC.

To determine the effects of ageing on performance, the data of simulated office tasks were normalized; the maximum score of each subject was equal to 100% and all other scores of the subject were related to this score. After normalizing the data, the results of the simulated office tasks indicate a significant (LMM, $p<0.05$) effect of ageing on the number of completed additions and the number of correct additions. In general, the percentage of completed additions was approximately 15-20% higher for the young adults in comparison to the elderly; the percentage of correct additions was approximately 5% higher for the young subjects. Within the groups no significant differences as a result of temperature changes were observed. In addition, no significant differences were found between the parts of the measurement session; time-effects or the type of slope (increasing or decreasing) did not have a significant influence.

5.7.4 Discussion

Based on the experimental results for the control situation it was possible to distinguish between effects of a constant room temperature and transient conditions. The temperature drifts were significantly noticeable for the young subjects (significant differences between session 1 and 2). Based on results of the questionnaire, the studied moderate temperature drifts did not result in unacceptable thermal conditions. Furthermore, the results of the individual parts (I and II) show that thermal sensation (TS) and thermal comfort (TC) were not affected by time.

No significant differences in thermal sensation and thermal comfort were observed between the increasing (part I) and decreasing ramp (part II) for both the elderly and younger adults; subjects did not distinguish between both ramps.

During the stable temperature condition (S1) thermal sensation was related to skin temperature for both subjects. However, during the moderate temperature drift (S2) TS of the elderly was mainly related to air temperature, while TS of the younger adults was related to skin and air temperature. Thermal comfort was related to skin temperature for both conditions (S1 and S2).

Fiala (1998) derived a relation between thermal sensation, mean skin temperature, core temperature and the change in mean skin temperature. In this study, for the elderly subjects, a significant relation was found between air temperature, the extent of vasomotion and core temperature. For the young adults a significant relation was found between air temperature, core temperature and mean skin temperature. The experiments which Fiala used to derive the relation between physiological parameters and thermal sensation were conducted with young subjects (college-age students). Therefore, the results can be compared only with results of the young adults in this study. In this study no influence of the rate of change in mean skin temperature on thermal sensation of the young adults was observed. Fiala originally included this term to account for rapid (e.g. step-wise) changes in ambient temperature. However, in this study the temperature changes can be considered as relative slow changes in ambient temperature which did not cause an immediate change in skin temperature.

Predictions of the thermal sensation obtained with the PMV model showed good agreement with the measurement results for the young adults. For the elderly, conversely, a difference of 0.5 scale units was found between predicted and measured TS. The trends, however, were in good agreement.

The results of the simulated office tasks revealed that ageing had a significant, negative effect on performance; the average normalized performance was 5-20% lower for the elderly in comparison to the young adults. Office work normally covers a wide range of different tasks involving a complex set of component skills. Typical tasks include text typing and different types of arithmetical calculations. If these tasks are affected by changes in the indoor environment, it is reasonable to assume that office work in general will be affected similarly.

Importantly, the temperature changes did not affect the productivity, which is in line with results from Seppänen and Fisk (2005) and Tanabe (2006).

The results of the subjective responses obtained from the experiments carried out within this study support the premise that the optimum conditions for elderly differ from those of their younger counterparts, which is contrary to ASHRAE (2009). However, more recent studies by, among others, Collins et al. (1981), Hashiguchi et al. (2004) and DeGroot and Kenny (2007), also revealed that the optimum conditions for elderly differ from the optimum conditions for young adults. Elderly are more vulnerable, compared to young adults, in conditions that differ from neutral, because the efficiency of their cold-and warm-defence mechanisms has declined and the ability to detect, and therefore respond to, temperature changes is reduced. Furthermore, Poehlman et al. (1994) revealed that their metabolic rate is lower compared to the metabolic rate of younger people due to a decrease in muscle mass which reduces both the basal and resting metabolic rate.

The thermal sensation of the elderly was in general 0.5 scale units lower than TS of the young adults. The same trend was found for the thermal comfort votes; the elderly felt less comfortable than the young adults. During session S1 with the stable temperature condition (21.5ºC) the elderly preferred a higher temperature, while the young adults requested no change in temperature. The difference in thermal sensation may be explained by a decreased thermoregulatory response (especially the vasoconstrictor response), indicated by the extent of vasomotion measured by the differences in skin temperatures between the young adults and the elderly (Anderson et al., 1996; van Someren, 2007; DeGroot and Kenny, 2007). During the experiments the elderly were continuously more vasoconstricted (i.e. the skin temperature of the fingertip was mostly lower than the skin temperature of the underarm) in comparison to the young adults.

In this study no significant correlation was found between the extent of vasomotion or fingertip temperature and thermal sensation parameters, although a relation in literature was found between these parameters. Wang et al. (2007) found that finger temperature (30°C) and finger-forearm gradient (0°C) are significant thresholds for overall thermal sensation. The experiments in the present study were conducted under cooler environmental conditions in comparison to the majority of the experiments in the study by Wang et al. (2007) ($T_{neutral}$ in the present study was 21.5°C versus 25.8-27.1°C in Wang et al.). Since the hands were not covered during both studies, this resulted in significantly lower fingertip temperatures in the present study. Based on the results obtained in the present study one could conclude that both fingertip temperature and fingertip-forearm gradient are not applicable as thermal sensation predictors under conditions were the body is nearly continuously in vasoconstriction mode (fingertip-forearm gradient >0°C). In conditions where the temperature range is larger it probably can be used as predictor for thermal sensation.

In this study a significant correlation with the extent of vasomotion was found only for thermal comfort.

It has been mentioned that for the elderly subjects healthy retired persons were selected who were normotensive and not taking any medications that might alter the cardiovascular or thermoregulatory responses to the temperature changes. The question is whether these healthy elderly subjects are representative for the elderly population because most elderly use medication. For instance, in The Netherlands in 2008 nearly 73% of the males in the age of 65 years and older were normotensive and taking medication that might alter the cardiovascular or thermoregulatory responses (CBS, 2009). It is possible that the differences in thermal physiology and thermal comfort, between the majority of the elderly population and the young adults, are larger than reported in this study.

5.7.5 Conclusions

The present study investigated the differences between young adults and elderly in thermal comfort, productivity and thermal physiology in response to a moderate temperature drift. From the presented results the following conclusions can be drawn:

- thermal sensation of the elderly is in general 0.5 scale units (on a 7-point thermal sensation scale) lower than thermal sensation of younger adults;

- during a constant temperature level and equal clothing level, elderly prefer a higher ambient temperature in comparison to their younger counterparts, which is in line with previous studies;

- in this study, the PMV model was capable of predicting thermal sensation (TS) of young adults in response to a moderate temperature drift which is in line with results obtained by previous studies. For elderly, the model was capable of predicting the trends in thermal sensation. However, the thermal sensation vote is overestimated with 0.5 scale units; and therefore, for example, the predicted TS corresponds to a sensation equal to neutral, while they will actually feel slightly cool;

- although the subjects were feeling less comfortable during the temperature drift in comparison to a constant temperature level, the conditions did not lead to unacceptable situations, i.e. the studied conditions were not unacceptably uncomfortable. Furthermore, productivity was not negatively influenced by the temperature changes. Therefore, a temperature drift up to ±2 K/h in the range of 17-25°C is assessed as applicable and will not lead to unacceptable conditions.

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