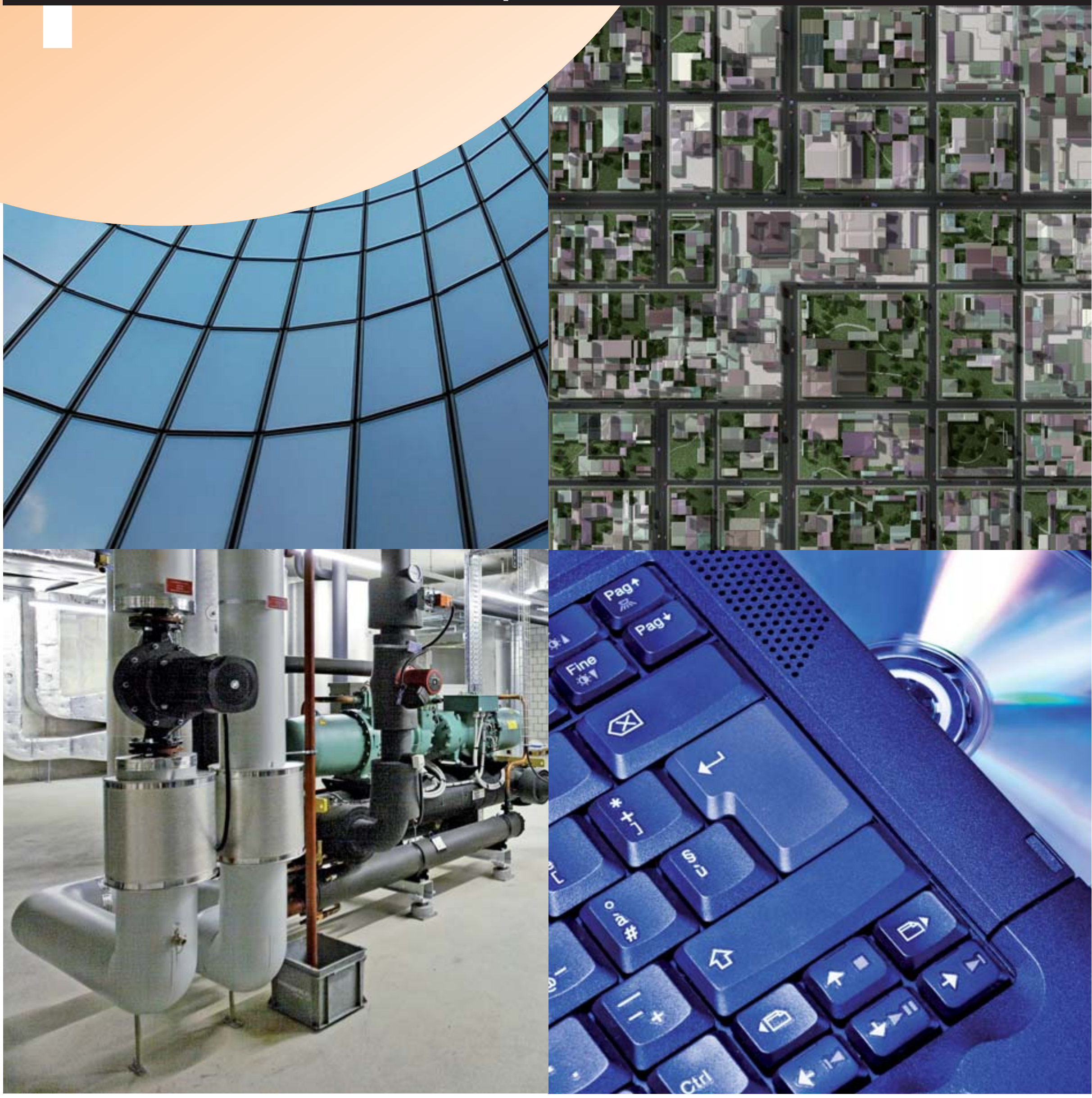
ECBCS Annex 49

report

Low Exergy Systems for High-Performance Buildings and Communities

Annex 49 Final Report



"Detailed Exergy Assessment Guidebook for the Built Environment"

Edited by Herena Torio and Dietrich Schmidt

International Energy Agency
Energy Conservation in Buildings and Community Systems Programme

Participating countries in ECBCS:
Australia, Austria, Belgium, Canada, P.R. China, Czech Republic, Denmark, Finland, France, Germany, Greece, Italy, Japan, Republic of Korea, the Netherlands, New Zealand, Norway, Poland, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom and the United States of America.

Further information about the ECBCS programme may be obtained from www.ecbcs.org

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PREFACE

International Energy Agency (IEA)

The International Energy Agency was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster co-operation among the twenty-four participating IEA countries and to increase energy security through energy conservation, development of alternative energy sources and energy research, development and demonstration (RD&D).

Energy Conservation in Buildings and Community Systems (ECBCS)

The IEA co-ordinates research and development in a number of areas related to energy. The mission of one of those areas, the ECBCS - Energy Conservation for Building and Community Systems Programme, is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research.

The research and development strategies of the ECBCS Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Building Forum Think Tank Workshop, held in March 2007. The R&D strategies represent a collective input of the Executive Committee members to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy conservation technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in three focus areas of R&D activities:

- Dissemination
- Decision-making
- Building products and systems

The Executive Committee (ExCo)

Overall control of the program is maintained by an Executive Committee, which not only monitors existing projects but also identifies new areas where collaborative effort may be beneficial. To date, the following projects have been initiated by the executive committee on Energy Conservation in Buildings and Community Systems (completed projects are identified by (*)):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)

Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings
Annex 48: Heat Pumping and Reversible Air Conditioning
Annex 49: Low Exergy Systems for High Performance Buildings and Communities
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings
Annex 51: Energy Efficient Communities
Annex 52: Towards Net Zero Energy Solar Buildings
Annex 53: Total Energy Use in Buildings: Analysis & Evaluation Methods
Annex 54: Analysis of Micro-Generation & Related Energy Technologies in Buildings
Annex 55: Reliability of Energy Efficient Building Retrofitting (RAP-RETRO)
Annex 56: Energy and Greenhouse Gas Optimised Building Renovation

Working Group -
Energy Efficiency in Educational Buildings (*)

Working Group -
Indicators of Energy Efficiency in Cold Climate Buildings (*)

Working Group -
Annex 36 Extension: The Energy Concept Adviser (*)

Working Group -
Energy Efficient Communities

(*) – Completed

IEA ECBCS ANNEX 49

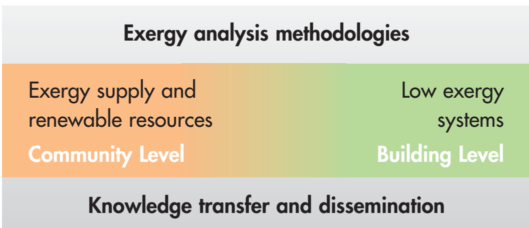
ECBCS Annex 49 was a three year international research project which arose from the discussions held in a Future Building Forum in Padova in April 2005. The project began on November 2006 and ran until November 2009. It involved 22 research institutions, companies and universities from 12 countries, many of which are also members of the International Society of Low Exergy Systems in Buildings (LowExNet). The main objective of this project was to develop concepts for reducing exergy demand in the built environment, thus reducing the CO_2-emissions of the building stock and supporting structures for setting up sustainable and secure energy structures for this sector.

Specific objectives are to:

- to use exergy analysis to develop tools, guidelines, recommendations, best-practice examples and background material for designers and decision makers in the fields of building, energy production and politics
- to promote possible energy/exergy cost-efficient measures for retrofit and new buildings, such as dwellings and commercial/public buildings
- to promote exergy-related performance analysis of buildings, viewed from a community level.

Countries which participated in the IEA ECBCS Annex 49: Austria, Canada, Denmark, Finland, Germany, Italy, Japan, the Netherlands, Poland, Sweden, Switzerland, and the United States of America.

The work within Annex 49 is based on an integral approach which includes not only the analysis and optimisation of the exergy demand in heating and cooling systems, but also all other processes where energy/exergy is used within the building stock. In order to achieve this, the project worked with the underlying basics, i.e. exergy analysis methodologies. The work items were aimed at development, assessment and analysis methodologies, and the development of a tool for the design and performance analysis of the regarded systems.



Structure of the ECBCS Annex 49

With this basis, the work on exergy efficient community supply systems was focused on the development of exergy distribution, generation and storage system concepts, as well as a collection of case studies. For the course of the project, both the generation and supply of and the use of energy/exergy were important issues. Resulting from this, the development of exergy efficient building technology depends on the reduction of exergy demand for the heating, cooling and ventilation of buildings. The knowledge transfer and dissemination activities of the project are focused on the collection and spreading of information on ongoing and finished work.

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Further information can be found in internet under:
www.annex49.com
or www.ecbcs.org/annexes/annex49.htm

The Guidebook of ECBCS Annex 49 is the result of a joint effort of many countries. We would like to gratefully acknowledge all those who have contributed to the project by taking part in the writing process and the numerous discussions. A list of the participants within Annex 49 and their corresponding countries can be found in the Appendix. All participants from all countries involved have contributed to the guidebook. However, the following annex participants have taken over the responsibility of writing the chapters:

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David Solberg	specially chapters 6 and 7

CONTENT

NOMENCLATURE

A	m^2	Area
a	-	Absorption coefficient
c	J/kgK	Specific heat capacity
ex	J/kg	Specific exergy
E	J	Energy
Ex	J	Exergy
F_Q	-	Quality factor
g	-	g-value; energy passage through glazing
G	kWh/m^2a	Incident solar radiation
h	J/kg	Specific enthalpy; heat transfer coefficient
H'_T	W/m^2K	Specific heat transmission coefficient
m	kg	Mass
M	W/m^2	Metabolic energy generation rate
$\dot{m}$	Kg/h	Mass flow rate
P	J	Electrical energy demand
p	Pa	Pressure
Q	J	Heat
R	J/kgK	Specific gas constant
s	J/kgK	Specific entropy
T	K	Temperature
t	s	Time
V	$(m^3/s)/m^2$	Volumetric rate
R	J/mol K	Gas constant

Greek characters

ε	-	Emissivity; Exergy effort figure
H	-	Energy efficiency
F	W	Heat flow
Ξ	W/m^2	Heat flux
Σ	$W/(m^2K4)$	Stephan-Bolzmann Constant
Θ	°C	Temperature
Ψ	-	Exergy efficiency
𝔐	g/mol	Molar mass
Ξ	-	Fan efficiency
Γ	-	Heat transfer effectiveness
ρ	Kg/m^3	Density

Index

0	Reference state
a	Air
active	Active
annual	Annual
aux	Auxiliary energy (electricity)
avg	Average
b	Building: black-body
boil	Boiler
C	Cold
c	Cooling; convective
Carnot	Carnot
cc	Cooling coil
ce	Emission
ch	Charging process
chem	Chemical
cl	Clothing
coll	Collector
cons	Consumed
cr	Core
cw	Condensed water
d	Distribution
design	Design
dot	Flow rate
DHW	Domestic hot water
DH	District heating
des	Desired
dem	Demand
disch	Discharge process
dry	Dry
dyn	dynamic
eff	Effective
el	Electricity; electric
env	Envelope
eqp	Equipment
FL	Full Load
flow	Flow
fuel	Fuel
g	Generation
gen	Generated
H	Hot
HP	Heating period
h	Heating
hc	Heating coil

heat	Heat
heater	herater
humid	Humid
i,j,e	Component
in	Inlet; inhaled
inf	Infiltration
int	Internal
intg	Integral
irrev	Irreversible, irreversibility
k	Time discretization index
L	Lighting
LMTD	Logarithmic mean temperature difference
ls	Losses
mech	Mechanical
matter	Matter
occ	Occupants
op	Operative
out	Outlet; exhaled
ove	Overall
p	Constant pressure
phys	Physical
preh	Preheating
prim	Primary
pump	Pumps
Q	Quality
r	Room-air
rad	Radiation
rat	Rational
ret (RET)	Return
s	Storage
sat	Saturation
SH	Space heaing
shell	Shell
single	Single
sk	Skin
sol	Solar
sto	Stored
steady	steady
sun	Sun
surf	Surface
syst	System
q-steady	Quasi-steady
sup (SUP)	Supply
t	Time
th	Thermal

th	Thermal
trans	Transmission
v	Vapor
vent	Ventilation
wall	Wall
w	Water
window	Window

1. INTRODUCTION

1.1 Background and Motivation

Environmental problems that have been linked to extended energy use, such as global warming, have raised a growing concern which has emphasised both the importance of all kinds of so-called "energy saving measures", and the necessity for an increased efficiency in all forms of energy utilisation.

The consumption of primary energy in residential and commercial buildings accounts for more than one third of the total worlds energy demand. This means that buildings are collectively a major contributor to energy related problems on a global scale. Despite the efforts made to improve energy efficiency in buildings, the issue of gaining an overall assessment, and comparing different energy sources still exists (Schmidt and Shukuya 2003). Current analysis and optimisation methods do not distinguish between different qualities of energy flows during the analysis. In the building codes of several countries, this problem has been solved by the transformation of all energy flows to the primary energy demand. An assessment of energy flows from different sources is first carried out at the end of the analysis by multiplying the energy flows by the primary energy factors. The primary energy factors necessary for the calculation have been derived from statistical material and political discussion and are not based on analytical grounds or on thermodynamic process analyses. All energy conversion steps from the extraction of energy sources (e.g. fuels) to the final demands are assessed in the primary energy method; however, no information on the quality of the supplied energy and its relation to the required energy demands can be obtained through this assessment.

The quantity of energy is given by the first law of thermodynamics, and is calculated from energy balances for a system. Current energy systems in buildings are designed and improved based on this law. This means that the quantity of energy supplied is matched with the quantity of energy required. Highly efficient condensing boilers, with energy efficiencies of up to 98% are a straightforward result of such an analysis framework.

The quality of energy, is given, in turn, by a combined analysis of the first and second laws of thermodynamics. From these combined analyses, the thermodynamic concept of exergy is derived. Exergy represents the part of an energy flow which can be completely transformed into any other form of energy, thereby depicting the potential of a given energy quantity to perform work or, in other words, its quality.

In every energy system, some part of the exergy supplied to the system in question has to be "consumed" or destroyed. In the case of the highly efficient boilers mentioned above when used to supply low temperature heat, the potential of the fuels fed into the boiler is almost completely lost in the burning process. Due to this loss of energy potential, a large consumption of exergy occurs. Exergy efficiencies for such building systems (e.g. condensing boilers) are lower than 10%.

A combined energy and exergy assessment permits a clear understanding of the importance of moving away from burning processes for supplying the energy demands in buildings, and paves the way for a new technique of designing energy supply systems in buildings based on the use of renewable and low temperature heat sources.

1.2 The exergy approach

Most of the energy used in the building sector is required to maintain constant room temperatures of around 20°C. Since the required temperature levels for the heating and cooling of indoor spaces are low, the quality of the energy demanded for applications in room conditioning is naturally low ($q \approx 7\%$) . Different levels of energy quality are needed for different appliances within a building. If the production of domestic hot water is considered as heating water up to temperatures of about 55°C, the energy quality needed is slightly higher than that of heating a room to 20°C ($q \approx 15\%$). For energy applications such as cooking heating a sauna, an even higher quality level is needed ($q \approx 28\%$). For the operation of different household electrical appliances and lighting the highest possible quality of energy is needed ($q \approx 100\%$).

Today's energy supply structure is not as sophisticated as today's energy demands. Energy is commonly supplied as electricity or as a fossil energy carrier and the energy quality of the supply for all different uses is at a constant value of ($q \approx 100\%$), a value that is unnecessarily high (see Figure 1.1, left). Similarly as in the case of a boiler mentioned above, the typical primary energy efficiency of the heating process in Germany is approximately 70% for heating newly erected dwellings that are equipped with good building service systems. This level of efficiency decreases to approximately 10% when considering exergy.

In turn, an adaptation of the quality levels of supply and demand could be managed by covering, for example, the heating demand with suitable energy sources, as available district heating with a quality level of about 30%. Other appropriate low exergy

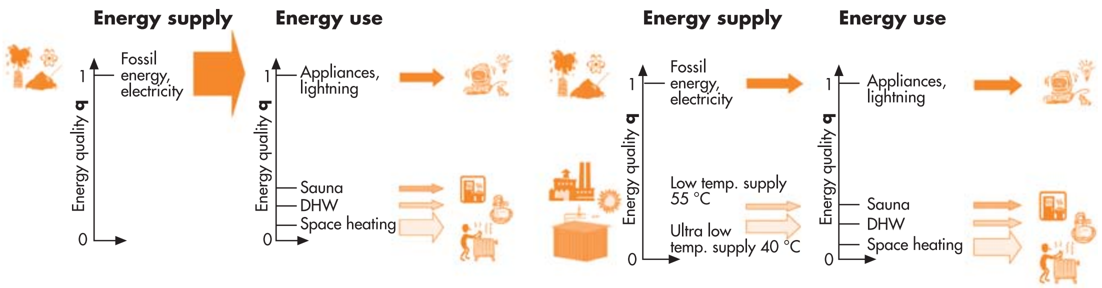


Figure 1.1: Left: Energy supply by means of high quality energy sources for a typical building with several uses at different quality levels. Right: Energy supply with sources at different quality levels for the same building with uses at different quality levels.

sources (i.e. low temperature sources) are solar or ground source heat. By using these sources, quality levels of the energy demanded and supplied are adapted to each other as shown in the right diagram of Figure 1.1.

New low temperature heating and cooling systems are required to make energy use in buildings even more efficient by supplying energy with low quality and creating the possibility of using renewable energy sources. There is a large variety of such emission systems solutions on the market, e.g. waterborne floor heating systems, that can be used to supply buildings with the lowest possible supply temperatures (q ≈ 13%). Furthermore, it has been found that when low temperature systems are applied to buildings, the thermal indoor comfort is improved at the same cost level as by using conventional, less comfortable building service systems (IEA Annex 37, 2002).

The methodology and models behind complex dynamic exergy simulations which have been developed within the Annex 49 project are presented in this report. It should be noted that a simplified steady-state analysis has proven to be adequate for the first estimations on the performance of different building systems. Additionally, several simplified and user-friendly tools that grant building planners, architects, and other decision makers of the built environment access to an exergy-based building approach have been developed within Annex 49 and are also introduced in this report.

1.2.1 Benefits and outcomes: why exergy?

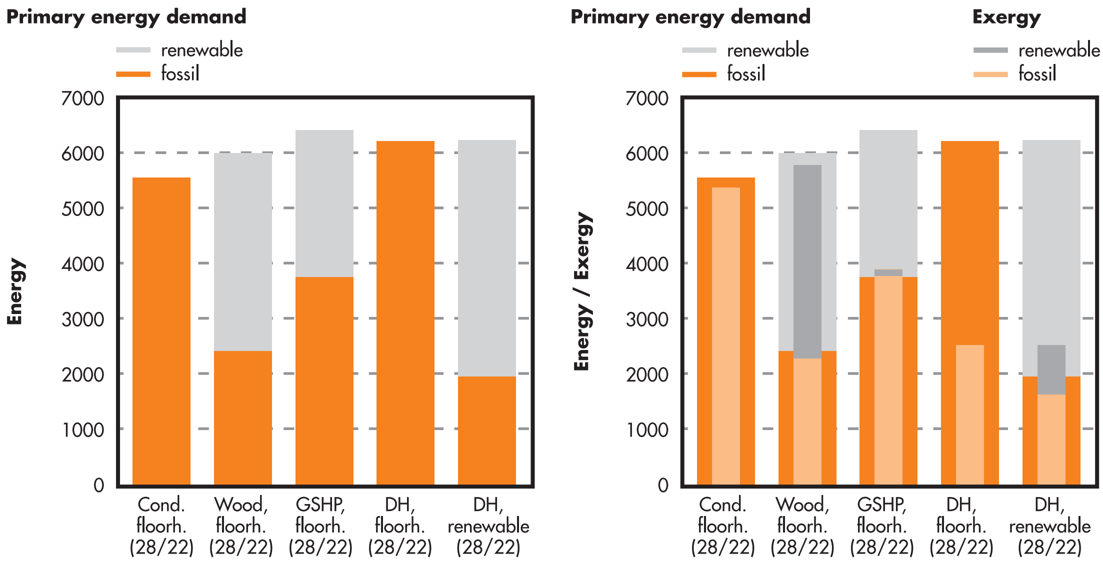
As previously stated, all assessments of energy utilisation in buildings are based solely on quantitative considerations. The LowEx analysis approach will take the methods of building energy assessment a step further by considering not only the quantitative aspects of demand and supply, but the qualitative aspects as well.

The following simple example shows how an exergy analysis can help building designers choose more efficient energy supply systems. Figure 1.2 shows the results from a simplified exergy analysis on a building case study. Different energy supply systems have been considered to supply the low-exergy demands for space heating and DHW. Primary energy analyses focus on the maximum possible use of renewable energy sources. Based on the criteria from primary energy analysis the input of fossil energy sources needs to be minimized. Following, the wood pellet boiler would be the best performing solution, allowing minimum use of primary fossil energy.

Exergy analyses aim additionally at minimizing both the fossil and renewable exergy input for a given system. An exergy analysis promotes an efficient energy supply, while highlighting that even renewable energy sources need to be used efficiently. Figure 1.2 depicts the exergy input of a wood-based boiler as being the largest of the four options. This is because wood is a high-quality energy source even though it is renewable and the efficiency of wood boilers is not yet as high as that of conventional liquefied gas condensing boilers. The fact that the exergy input is the largest indicates that such an energy supply does not promote an efficient use of the potential of the energy sources used. As a high-quality energy source, wood could be used instead for supplying high exergy demands such as electricity generation. In this way, wood as a fuel would be used to its fullest potential. The use of wood in a CHP unit, using the waste heat from the power generation process for low-exergy applications, allows minimum exergy input and minimum fossil energy input.

A deeper understanding of the nature of energy flows and/or conversion processes in buildings would enable building designers and architects to achieve an improved overall design.

Based on the example and considerations above, the main benefits of joining considerations on the quantity and quality of energy supply, i.e. of exergy analysis, can be summarized as:



Where:	
Cond.	Natural gas fired condensing boiler
Wood.	Wood pellet boiler
GSHP	Ground source heat pump
DH	Waste district heat
Floorh.	Floor heating system

Figure 1.2: Calculated primary energy demand (fossil and renewable) and the related exergy for different supply options of a building case study. Results correspond to steady state calculations performed with the Annex 49 pre-design tool (see chapter 3).

- Exergy analysis clearly shows the importance of promoting a more efficient use of fossil fuels. Systems such as highly energy efficient boilers would always be avoided following this approach. CHP systems, using better the high potential (i.e. quality) of fossil fuels would be promoted instead.

- The above conclusion is also valid for renewable energy sources with high thermodynamic potential (i.e. high exergy sources), as shown in the example presented (Figure 1.2). Thereby, exergy analysis also promotes an efficient use of limited available renewable sources such as biomass.

- Exergy analysis highlights the importance of using low temperature renewable energy sources available to supply heat demands in buildings.

- Low temperature and high temperature cooling systems in buildings are exergy efficient emission systems, that allow the integration of renewable sources. The exergy performance of these systems is significantly higher than for conventional air based or high temperature heating and low temperature cooling systems. Thereby, exergy analysis is an appropriate tool for integral building design, allowing to see the benefits of efficient energy use in every conversion step of the supply chain.

1.3 Target group

This full report of ECBCS Annex 49 is oriented mainly for scientists and researchers working in the field of energy efficient building systems. The technical background and thermodynamic concepts related to the exergy analysis in building systems are explained thoroughly in a clear and detailed way in this report. The report is intended to present state-of-the-art related to exergy analyses in buildings.

Over the past years, exergy analyses of building systems have become more prevalent in scientific literature; however, exergy analysis in buildings (particularly dynamic exergy analysis) is a controversial issue and is very sensitive to the assumptions made by the user. This report is intended to be a reference for further analyses so that a comparability can be guaranteed between the results of exergy analyses of different building case studies.

A summary of this report has been produced in order to bring the concepts and methodology of exergy analysis to building decision makers and planers. The technical details behind the exergy concept are explained in that short report in a simplified, applicable manner by focusing more on the outcomes of exergy analysis and the importance of this concept for building systems design. In addition, the main features of several building and municipal case studies highlight the importance and main benefits of this analytical approach. This summary report can be downloaded at www.annex49.com.

1.4 Main objectives and layout of this report

In this context, the main objectives of the ECBCS Annex 49 are to:

- Develop design guidelines regarding exergy metrics for performance and sustainability

- Create open-platform exergy software for building design and performance assessment

- Show best practice examples for new and retrofit buildings and communities

- Document benefits of existing and developed demonstration projects

- Set up a framework for future development of policy measures and pre-normative work including the exergy concept

The present extended version of the ECBCS Annex 49 Guidebook shows final research outcomes from the joint international research activities within the Annex 49 group. The topics mentioned above are treated in detail in the following chapters. Chapter 2 gives a detail description on the first unitary methodology for performing dynamic exergy analysis on building systems. There, fundamental concepts and the thermodynamic background of the exergy approach are highlighted besides detailed equations for analysis of several building systems. In chapter 3 the tools developed within the work of Annex 49 are presented. A detail description of the main features, calculation approach and usability of each tool is also given. Chapter 4 highlights and summarizes the main strategies for an exergy optimized design of buildings and community systems. Chapter 5 presents the main parameters developed or used here for characterising exergy performance of any building or community. Based on these parameters, the first discussions and bases for setting pre-normative proposals that include the exergy concept are also included. Chapters 6 and 7 show the main building and community case studies analyzed within the research activities of the ECBCS Annex 49.

2. METHOD AND MODELS FOR EXERGY ANALYSIS

In this chapter the method and mathematical models developed for exergy analysis of building systems within the ECBCS Annex 49 group are introduced. Exergy analysis is a thermodynamic method which has been applied commonly since mid of last century to e.g. complex power generation systems. Yet, energy processes in power plants and buildings are significantly different: whereas in power stations energy processes are often far from environmental conditions, thermodynamic variables in the energy processes in buildings are very close to (outdoor) ambient conditions. Thus, for the application of the exergy method to the built environment several adjustments and adaptations are required.

This chapter begins with a review of the main thermodynamic fundamentals behind exergy analysis. In section 2.1, several fundamental concepts such as the exergy concept, the reference environment or sign convention applied are explained in direct relation to energy processes in buildings. Quality factors are often used to characterise the exergy content of a given energy flow. They adopt different expressions depending on the energy processes regarded. The different quality factors that are applied to thermal energy processes are also presented in section 2.1.

In section 2.2 the method used here to derive models for exergy analysis in buildings is introduced. For this aim, firstly the main assumptions and simplifications (such as the input-output approach) on which the method is based are presented. The method described here can be applied in different levels of complexity and detail. Equations presented in section 2.3 can be used for steady-state, quasi-steady state or dynamic exergy analysis. The difference between these approaches is clarified in section 2.2.1.

Similarly as the energy demand of buildings, the exergy demand of a building is one of the most important variables of exergy analysis in buildings. The exergy demand represents the minimum amount of work that would need to be provided to the building in order to keep acceptable conditions in the indoor environment. Within ECBCS Annex 49 two different approaches have been developed for determining the exergy demand of buildings: a simplified approach, suitable for analyzing the efficiency and performance of building systems, and a detailed approach suitable for analyzing the performance of the building design and envelope. Both approaches are presented in detail in section 2.2.2. The detailed equations developed and implemented in models for dynamic exergy analysis of energy processes in building systems are introduced in section 2.3.2. Buildings are erected to be comfortable living spaces and provide adequate shelter to their occupants. Thus, models related to the exergy of human thermal comfort have also been developed and are included at the beginning of that section. A detailed description of models for dynamic exergy analysis of several building systems follows. Finally, a simplified method developed for exergy analysis of community supply systems is introduced. Main results of the method, applied to a case study in Germany, are also introduced in section 2.3.4.

2.1 Applied fundamentals

This section describes the exergy fundamentals in such a way that they can be applied for the analysis of the energy supply systems in buildings. For a more general introduction to exergy we refer to the final report from the previous Annex on the topic, Annex 37 guidebook (Ala-Juusela, 2003).

2.1.1 Definitions

Exergy is a measure of the quality of energy. Work is energy with the highest quality, which can be totally converted to any other type of energy. In thermodynamics 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 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, in such a way that finally equilibrium with the environment is achieved.

This definition shows that all systems in a state different from the environmental state contain exergy, or in other words have the ability to produce work. The exergy of a system can consist of the following components:

- Chemical exergy (due to a difference chemical composition)
- Thermal exergy (due to a difference in temperature)
- Mechanical exergy (due to a difference in pressure)

For heating and cooling purposes mostly the thermal exergy is of importance. Therefore in this chapter the focus is on thermal exergy. However, chemical and mechanical exergy can play a role in certain situations. Therefore these are also mentioned in some cases.

Heat is the transfer of energy between two systems as a result of a difference in temperature. This energy is not related to matter. When analyzing one system, heat is the transfer of energy across the system boundary, taking place at the temperature of the system boundary. The word cold is used to refer to heat at temperatures below the environmental temperature T_0. The exergy of heat is the theoretical maximum work that can be obtained by bringing the heat in thermal equilibrium with the environment using a reversible process. The ratio between the exergy (Ex) and energy of the heat transferred (Q), is defined as the quality factor. In literature the quality factor is also called "exergy factor" or "exergetic quality factor" (Dincer and Rosen 2007). The quality factor illustrates the work potential per unit heat and thereby it indicates its quality.

Thermal energy is contained by matter. It is the part of its internal energy associated with temperature, including both sensible and latent heat. As described by Shukuya (Shukuya 2009) there can be both a surplus of thermal energy relative to the environment (the system is warmer than the environment) or a lack of thermal energy relative to the environment (the system is colder than the environment). A thermal energy surplus relative to the environment can be called "hot thermal energy" and a thermal energy deficit relative to the environment can be called "cold thermal energy".

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

- $Q > 0$ = Heat transfer to a system;
  $Q < 0$ = heat transfer from a system.
- $W > 0$ = Work done by a system;
  $W < 0$ = work done on a system.

The sign of the heat or work is thus dependent on the defined system, which shows the importance of defining the system under consideration and its boundaries.

Exergy is never supplied to or removed from a system as exergy; it is always accompanying other forms of energy transfer. The sign convention for exergy accompanying heat is:

$Ex_Q>0$ = Exergy transferred to the system;
$Ex_Q<0$ = exergy transferred from the system

2.1.2 Reference environment

2.1.2.1 Definition

The thermodynamic reference environment for exergy analysis is considered as the ultimate sink of all energy interactions within the analyzed system, and absorbs all generated entropy within the course of the energy conversion processes regarded (Baehr, 2005). The environment needs to be in thermodynamic equilibrium, i.e. no temperature or pressure differences exist within different parts of it (thermomechanical equilibrium). Chemical equilibrium must also be fulfilled. Furthermore, intensive properties of the environment must not change as a result of energy and mass transfer with the regarded energy system (Baehr, 2005). In addition, the reference environment is regarded as a source for heat and materials to be exchanged with the system to be analysed (Dincer, Rosen, 2007), i.e. it must be available and ready to be used by the system under analysis.

The reference environment is also be described as that portion of the surroundings of a system, of which the intensive properties of each phase are uniform and do not change significantly as a result of the process under consideration (Bejan, et al. 1996). It can thus act as either an unlimited sink or unlimited source.

2.1.2.2 Discussion: Possible choices

Several choices for the reference environment can be found. However, Wepfer and Gaggioli (1980) clearly stated that the reference environment for exergy analysis, unlike reference variables for thermodynamic or thermo-chemical tables, cannot be chosen arbitrarily. The reason is that energy analysis is based on a difference between two states and, thus, the chosen reference levels out in the balance. In turn, in exergy analysis the chosen reference does not level out in the balance and values of the e.g. absolute temperature chosen as reference strongly influence results from exergy analysis.

In this section a discussion on their physical and thermodynamic correctness is presented. In order to show the influence of choosing one reference environment or another for exergy analysis, steady-state exergy analyses have been carried out on a building case study. Analyses with the four different options for the reference environment introduced below have been performed with the pre-design Excel tool developed within ECBCS Annex 49. Exergy and energy flows obtained with the different reference-environments are shown graphically in Figure 2.1.

a) The universe (nearly zero Kelvin) as reference environment

The temperature of the universe is very low, around 3 degrees Kelvin. This allows radiative energy transfer from the earth and, thus, discarding of entropy produced as a result of energy processes on earth (Shukuya and Komuro,1996). From a first law (or energy conservation) perspective, the earth is an open system receiving a net energy flux from the sun in the form of high quality solar radiation, tidal energy from celestial bodies and geothermal energy from nuclear processes within the earth crust (Sørensen, 2004), being the energy from solar radiation the greatest input. All energy incoming from the sun is ultimately radiated (or reflected) back into the universe (Rosen, 2002): about one fourth is reflected in the form of light (high quality, short wave radiation) and three fourths are emitted in the form of low-temperature heat (low quality, long wave radiation) (Szargut, 2005; Shukuya and Komuro, 1996). Exergy balances for these processes can be found in (Szargut, 2003 and 2005). The emission of low temperature heat, occurring since the sky temperature is lower than the mean temperature of the earth, allows for the discarding of the entropy produced through the degradation of the incident solar radiation and keeps the so-called "exergy-entropy" process on the global environment (Shukuya and Komuro,1996). It could be regarded, therefore, as the ultimate sink of energy processes within a building. It is infinite and undergoes no variation in its intensive properties as a result of heat and mass transfer processes within the building.

However, cool radiation from the universe is not always directly available and ready to be used by the built environment (otherwise no cooling energy would be required). This is shown in Figure 2.1 (a). Thermal energy and exergy flows (from storage system to the building envelope) are equal. Differences in the "Generation" and "Primary energy transformation"[2] subsystems occur due to quality factors for liquefied natural gas (LNG), regarded as 0.94 (Szargut and Styrylska, 1964)[3].

b) Indoor air inside the building

Indoor air within the building has also been proposed as reference environment for exergy analysis. However, indoor air is neither an infinite sink nor is it in thermodynamic equilibrium. In addition, its temperature varies as a result of energy processes within the building. Therefore, it does not fulfil the requirements for being regarded as a thermodynamically correct reference environment[4].

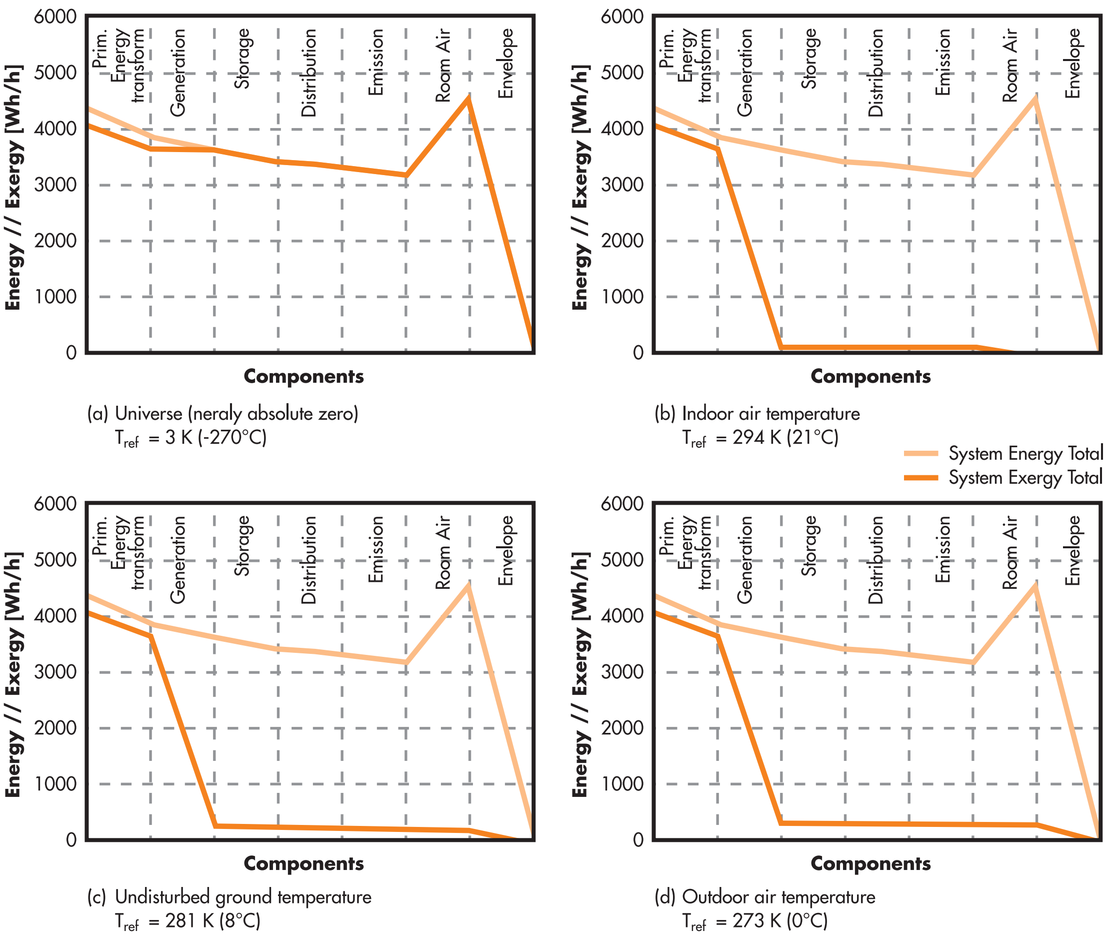


Figure 2.1: Energy and exergy flows for a building case study with the four introduced reference environment options.

Results using indoor air as reference environment are shown in 2.1 (b). As shown in Figure 2.1 exergy demand of the building (input in the "envelope" subsystem) is zero, for it is regarded as reference environment. In consequence, this approach does not allow deriving exergy efficiencies for the overall energy supply in buildings since the desired output would always be zero.

c) Undisturbed ground

The undisturbed ground can also be proposed as reference environment for building exergy analysis. It can be regarded as infinite sink, whose properties remain uninfluenced as a result of interactions with the building. Yet, the main objection for regarding it as reference environment, similarly as the absolute zero, is that it is not always directly available and ready to be used by the built environment[5].

d) Ambient air surrounding the building

Most energy processes in the building sector occur due to temperature or pressure differences to the surrounding air. Thus, the air surrounding the building can be regarded as the ultimate sink (or source) for the energy processes occurring in the building. On the other hand, the air volume around the building can be assumed to be big enough (infinite sink) so that no changes in its temperature, pressure or chemical composition occur as a result of the interactions with the building. In addition, outdoor air surrounding the building is naturally available and ready to be used[5].

2.1.2.3 Conclusion & Recommended reference environment

It is recommended to use the (current) surrounding outdoor air as the reference environment for exergy analysis of buildings and their energy supply systems, since this is the only system that:

- is unlimited (either acting as a sink or a source),
- is unchanged by the processes that are regarded,
- and is always available.

However, outdoor air temperature and pressure do vary with time and space, i.e. external air is not a homogeneous system in thermo-mechanical or chemical equilibrium.

As stated in (Dincer and Rosen, 2007) "the natural environment is not in equilibrium and its intensive properties exhibit spatial and temporal variations. Consequently, models for the reference environment are used which try to achieve a compromise between theoretical requirements and the actual behaviour of the reference environment". In order to model the outdoor air surrounding a building as a thermodynamic reference environment, temperature and pressure are assumed to be uniform for the air surrounding the building (thermal and mechanical equilibrium). Concentration of different chemical species in the atmospheric air is also regarded as homogeneous. A detailed analysis of different suitable reference environments can be found in (Sakulpipatsin 2008).

2.1.3 Exergy of heat

The exergy of heat is based on a reversible thermal power cycle (e.g. Carnot cycle) operating between a hot and a cold reservoir, see Figure 2.2. Heat (Q_H) is transferred to the system from the hot reservoir. From the second law it is known that not all heat to the system can be converted into work, but a certain amount ($-Q_C$) must be rejected to the cold reservoir.

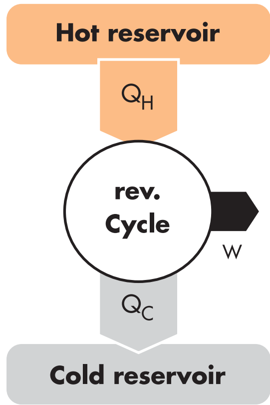


Figure 2.2: Scheme of a reversible thermal power cycle (e.g. Carnot cycle).

The work obtained from this cycle can be calculated using equations 2.1 and 2.2, based on the first and second law of thermodynamics respectively. For these equations Q_C is regarded as negative, according to the sign conventions.

$$W = Q_H + Q_C \tag{2.1}$$

$$\frac{Q_H}{T_H} = \frac{Q_C}{T_C} \tag{2.2}$$

The maximum amount of work for a given Q_H and given temperatures can be calculated with (2.3). The factor $(1-T_C/T_H)$ is called the Carnot efficiency.

$$W = Q_H + Q_C = Q_H - Q_H * \frac{T_C}{T_H} = Q_H\left(1 - \frac{T_C}{T_H}\right) \tag{2.3}$$

2.1.3.1 From a reversible cycle to exergy calculation

While a reversible thermal power cycle describes a cycle between two reservoirs at arbitrary temperatures, the calculation of the exergy of heat is based on this cycle, but assumes the environment to be one of the reservoirs at environmental temperature (T_0). Whether T_0 acts as the hot or the cold reservoir depends on the temperature of the heat available related to the temperature of the environment. ($T>T_0$ or $T<T_0$). (see Figures 2.2 and 2.3). For simplicity the source containing hot (=energy surplus, "H" in the diagram and equations 2.2 and 2.3) or cold (= energy deficit, "C" in the diagram and equations 2.2 and 2.3) thermal energy is considered to have a constant temperature while heat is being transferred (as would for example be the case with latent energy).

2.1.3.2 Heat transfer at $T>T_0$

Heat transfer at $T>T_0$ to the environment can be converted to work and thus "contains" exergy. This heat is in fact Q_H at T_H and the environment acts as T_C. Q_C (the heat disposed to the environment) is not known and depends on the temperatures. The exergy (Ex) and the quality factor (Ex/Q) of this available heat Q_H can be calculated using equation 2.4.

$$W = Q_H + Q_C = Q_H - Q_H * \frac{T_O}{T_H} = Q_H\left(1 - \frac{T_O}{T_H}\right) \quad (2.4)$$

2.1.3.3 Heat transfer at $T<T_0$ ("cold")

If heat transfer takes place to a cold "reservoir" (at constant T, $T<T_0$) this is in fact a possible disposal of heat Q_C at T_C. The environment then acts as a heat source at T_H. The value of Q_C is then the available cold (or in other words lack of thermal energy), while the value of Q_H is not known and can be calculated based on the temperatures. Calculating the exergy of Q_c can be done by using equation 2.5).

$$W = Q_H + Q_C = -Q_C * \frac{T_O}{T_C} + Q_C = Q_C\left(1 - \frac{T_O}{T_C}\right) \quad (2.5)$$

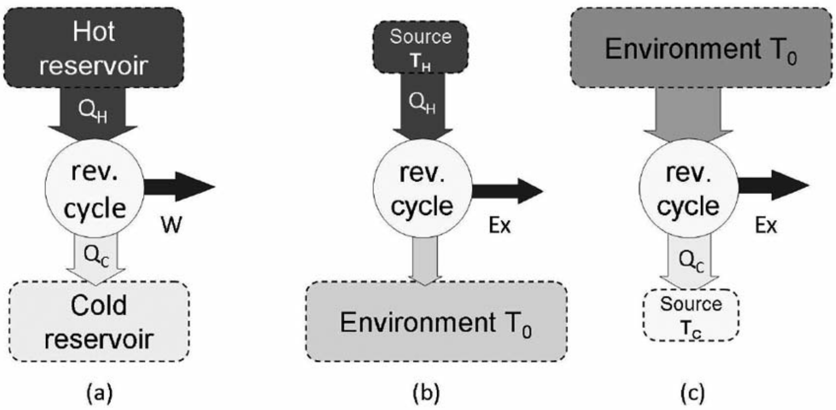


Figure 2.3: (a,b,c): Schemes showing the relation between a reversible thermal power cycle and the exergy of heat: (a) Reversible cycle, (b) heat available at $T>T_0$, T_0 acts as the heat sink, (c) heat ("cold") available at $T<T_0$, T_0 supplies heat.

2.1.3.4 General equation for exergy accompanying heat

Equations 2.4 and 2.5 have shown that the exergy of heat transfer for both $T>T_0$ and $T<T_0$ is calculated by multiplying the heat Q with the same factor $(1\text{-}T_0/T)$.

The exergy accompanying heat transfer can therefore generally be calculated using equation 2.6, which is also used in most textbooks. This equation is thus valid for both heat transfer at $T>T_0$ and heat transfer at $T<T_0$, where it is important to bear in mind that in the last case d_Q refers to the heat rejected to the cold source and is then a negative value.

$$dEx = dQ_{rev} * \left(1 - \frac{T_0}{T}\right) \quad (2.6)$$

2.1.4 The quality factor

The factor $(1\text{-}T_0/T)$ from equation 2.6 is called the quality factor of heat. It is also sometimes called 'exergetic temperature factor τ' (Dincer and Rosen 2007). It is defined as the exergy content of a system divided by the energy content. The exergy content indicates the quality of heat. In Figure 2.4 the quality factor of heat is shown for a given environmental temperature of 25 °C.

From this graph it can be seen that when T approaches infinity, the quality factor becomes unity, which means heat transfer at very high temperatures can theoretically totally converted to work. When $T<T_0$ quality factor is a negative value. From equation 2.6 it can be seen that this means the exergy has the opposite value of the heat transfer. Here it becomes really important to note that Q_C (heat transfer from the environment to a "cold" thermal energy source at $T<T_0$) is considered as a negative value, which means the exergy of this heat transfer has a positive value and thus the heat transfer could produce work. It also means that systems with cold thermal energy (a lack of thermal energy and thus a negative value), contain exergy, or in other words: When there is cold available it has a potential to do work. This can also be seen in Figure 2.4.

In Figure 2.4 it can also be seen that when T approaches 0 Kelvin, the quality factor becomes minus infinity. This means low temperatures (if available) can produce a large amount of work. It also means that in order to obtain low temperature a large amount of work has to be supplied.

2.1.4.1 Placing the quality factor between absolute brackets:

It has been shown the quality factor ($1-T_0/T$) results in a negative value for temperatures at $T<T_0$ (resulting in a positive exergy content for "cold", as explained above). However, many (building) professionals are used to regard cold thermal energy as a positive value. Therefore sometimes the quality factor is placed between absolute brackets (Wall and Gong 2001), resulting in equation 2.7. This way also a positive exergy value for heat transfer at $T<T_0$ is obtained. This leads to Figure 2.5.

$$dEx = \left|1 - \frac{T_0}{T}\right| \cdot dQ \qquad (2.7)$$

Equation 2.7 leads to an easier comparison of the quality factor at $T>T_0$ and $T<T_0$. However, it has to be used with care, since by placing the quality factor between absolute brackets information about the direction of the exergy (transfer) in relation to the heat transfer is lost. This will be further explained in the next paragraph.

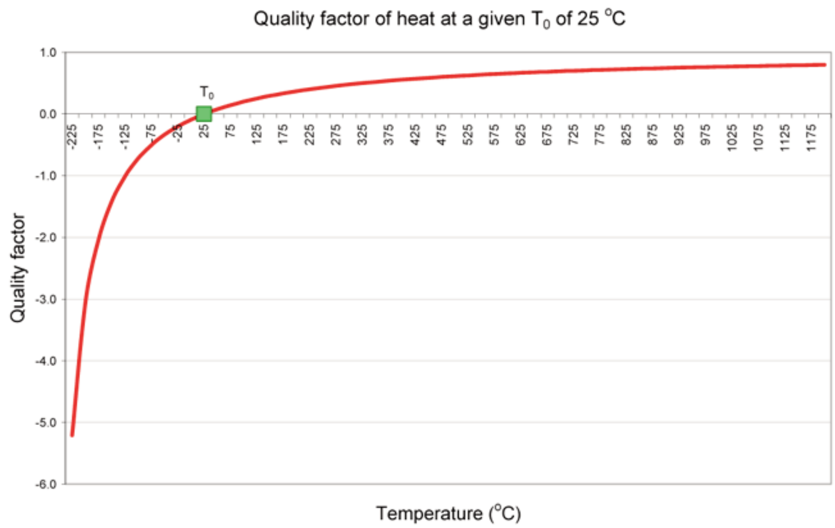


Figure 2.4: Quality factor of heat.

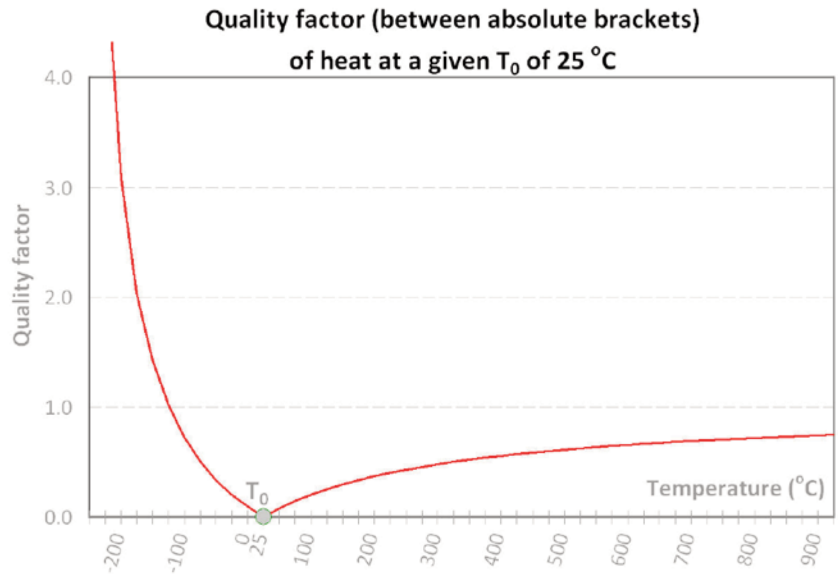


Figure 2.5: Quality factor of heat, placed between absolute brackets.

2.1.5 Heating and cooling processes: exergy input or output?

In the above paragraph the focus is on the exergy 'available' from heat. However, it depends on the direction of the heat flow and on the temperatures of the system and T_0, if a heat has the ability to produce work or requires the input of work. In general these rules are valid:

- Heat transfer bringing a system into equilibrium with the environment (and thus closer to T_0) can theoretically produce work. This means heat transfer that takes place spontaneously could produce work.
- Heat transfer bringing a system further from T_0 require work. (All non-spontaneous heat transfer requires work)

It can be helpful to picture an imaginary Carnot cycle between the environment and the heat transfer that is considered, in order to visualize if work has to be supplied or work can be obtained.

In the picture below the different options are shown:

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

The negative value for the exergy should not be understood as "negative work", but as an indication of the direction of the exergy into the system (i.e. exergy supply).

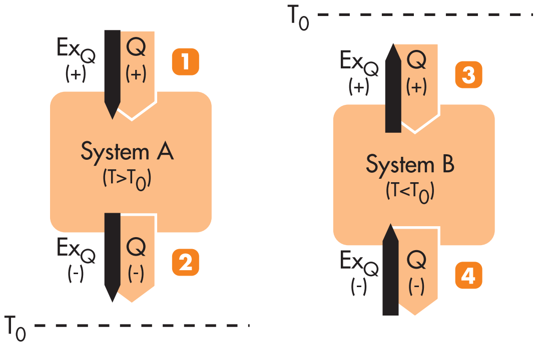


Figure 2.6: Direction of the exergy transfer related to energy transfer and temperatures T and T_0.

As can be seen from the figure the exergy accompanying heat transfer is in the same direction of the heat transfer in case of $T>T_0$, and in the opposite direction of the heat transfer in case of $T<T_0$. By using equation 2.6 (the equation with the quality factor without absolute brackets), the signs of the heat and exergy values will demonstrate whether they are inputs or outputs to the system. When using equation 2.7, the direction of the exergy and heat transfer is not shown in the sign of the results (since all results will be positive). Therefore, equation 2.7 has to be used with care and the direction of heat and exergy transfer has to be additionally determined by logical reasoning.

The previous part describes the exergy available from heat transfer or required to obtain heat transfer.

The thermal energy of matter, or the lack of thermal energy in case the matter is at $T<T_0$, always contains exergy, since there is no negative work (Wall and Gong, 2001). This means the air in a room, be it at $T>T_0$ or at $T<T_0$ contains warm or cool exergy, as is also explained by (Shukuya, 2009). However, to obtain air at $T \neq T_0$, exergy is required.

2.1.6 Exergy of radiative heat transfer

The radiative heat transfer from a surface at temperature T is given in the equation below:

$$Q_{rad} = \varepsilon \cdot A \cdot \sigma \cdot T^4 \qquad (2.8)$$

Where:

ε is the emissivity
A is the surface area [m²]
σ is the Stefan-Boltzmann constant of 5.67x10-8 [W/m²K⁴]

The radiative heat transfer between two parallel surfaces of the same area A at temperatures T_1 and T_2 is given in the equation below:

$$Q_{rad} = \varepsilon_{res} \cdot \sigma \cdot A \cdot \left(T_2^4 - T_1^4\right) \qquad (2.9)$$

ε_{res} = resulting emissivity of the two surfaces, according to:

$$\frac{1}{\varepsilon_{res}} = \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1 \qquad (2.10)$$

Estimating the exergy of thermal radiation has been a controversial issue and is still a matter of discussion in many scientific papers (Wright et al., 2002; Candau, 2003; Petela 2003). Candau (2003) presents in his work the derivation of the maximum work obtainable from a thermal radiant energy flow being emitted at a temperature T, regarding a reference environment at the temperature T_0.

The exergy of the radiative heat transfer between a surface and the environment can be evaluated using the following equation. This equation is in agreement with Wright et al. (2002) and Shukuya and Hammache (2002).

$$Ex_{rad} = \varepsilon_{res} \cdot \sigma \cdot A \cdot \left[\left(T^4 - T_0^4\right) - \frac{4}{3} T_0 \left(T^3 - T_0^3\right)\right] \qquad (2.11)$$

In equation 2.11 the emissivity factor ε is equal to the emissivity of the surface. The emissivity of the environment is assumed to be unity.

In equation 2.11 two types of irreversibilities are regarded (Petela, 2003):

- those derived from the conversion of thermal radiation at a temperature T into heat at the same temperature, T;
- and irreversibilities derived from the emission of radiation by the absorbing body at its temperature (T in equation 2.8).

2.1.6.1 The quality factor of radiative heat exchange

The quality factor of the exergy exchange between T and T_0 can consequently be calculated using:

$$F_{Q,rad} = \frac{\sigma\left[\left(T^4 - T_0^4\right) - \frac{4}{3}\left(T_0 T^3 - T_0^4\right)\right]}{\sigma\left(T^4 - T_0^4\right)} = 1 - \frac{4}{3}T_0\frac{\left(T^3 - T_0^3\right)}{T^4 - T_0^4} \quad (2.12)$$

In Figure 2.7 the difference between the quality factors corresponding to a conductive & convective heat exchange and those referred to a radiative heat exchange (equation 2.12) are shown. In this graph the quality factor between absolute brackets is shown, resulting in a positive value for both radiative heat transfer from a surface at $T>T_0$ to the environment and radiative heat transfer from the environment to a surface at $T<T_0$. Quality factors associated to radiative heat transfer are always lower, i.e. losses due to intrinsic irreversibilities associated to the radiative heat transfer process, as explained above, are bigger than for a conductive-convective heat exchange. It is important to remark that here a radiative heat transfer between a system at a temperature T and the environment at T_0 is being assumed. If instead, a smaller temperature difference is assumed for the radiative heat exchange (similarly to equation 2.13) is considered, the difference between both quality factors would be significantly lower.

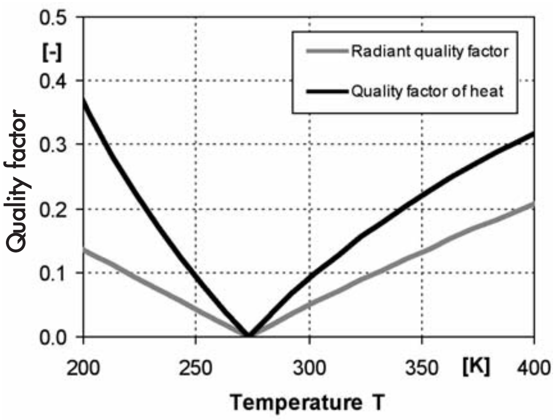


Figure 2.7: Graph showing the quality factor (between absolute brackets) of a convective heat transfer at T (black line) and radiative (light grey line) heat transfer between different temperatures T and T_0.

2.1.6.2 adiative heat transfer between two surfaces at T_{surf1} and T_{surf2}

Within a building radiative exchange occurs between e.g. two solid surfaces at two different temperature levels. In this situation radiative exchange at two different temperature levels (e.g. T_{surf1} and T_{surf2}) needs to be considered, including absorption and emission of thermal radiation at both temperature levels.

The general expression of the net radiative exergy transfer between two parallel surfaces is shown in equation (2.13). This is coherent with the conclusions shown in (Wright et al., 2002):

$$Ex_{rad} = \varepsilon_{res} \cdot \sigma \cdot A \cdot \left[\left(T^4_{surf1} - T^4_{surf2}\right) - \frac{4}{3}T_0\left(T^3_{surf1} - T^3_{surf2}\right)\right] \quad (2.13)$$

In this equation the emissivity factor ε is the resulting emissivity factor for both surfaces, as calculated in equation 2.10.

If the purpose of exergy analysis in buildings is to analyze and compare different heating and cooling systems, only radiative thermal heat transfer from the active heating or cooling element needs to be assessed in detail. Equation 2.14 can be applied for this aim.

$$Ex_{rad,active} = Q_{rad,active}\left[1 - \frac{4}{3}\frac{T_0}{\left(T^4_{surf,active} - T^4_{r,op}\right)}\left(T^3_{surf,active} - T^3_{r,op}\right)\right] \quad (2.14)$$

It is noted that in the case where the radiative heat exchange between two surfaces at T_1 and T_2 is considered and a smaller temperature difference is assumed for the radiative heat exchange than between T and T_0, (similarly to equation 2.13), the difference between both quality factors as shown in Figure would be significantly smaller. This is further explained in an example in paragraph 2.3.2.3.

2.1.7 Exergy of matter

An amount of matter which is not in equilibrium with the environment contains a certain amount of exergy. The exergy of matter consists of a thermal, mechanical, and chemical component, due to a difference in temperature, pressure and chemical composition respectively.

Different from the transfer of energy by heat, the thermal energy of matter can be regarded as a state of this matter. This state can be brought to equilibrium with the environment by heat transfer with the environment. The exergy of the thermal energy is equal to the exergy of the heat transfer that can be obtained. For latent heat the heat transfer takes place at constant temperature and therefore equation 2.6 can be used. For sensible energy however, the temperature of the heat transfer changes as the system (or matter) comes closer to equilibrium.

The sensible energy can be calculated using equation 2.15).

$$E_{th} = m \cdot c_p \cdot dT \qquad (2.15)$$

Assuming a constant value for c_p, the exergy of the (sensible) thermal energy of matter (also called Q) can consequently be calculated using equation 2.16 or equation 2.17 (see also: Bejan, et al. 1996; Wall and Gong, 2001)

$$Ex = \int_{T_0}^{T} m \cdot c_p \cdot \left(1 - \frac{T_0}{T}\right) dT \qquad (2.16)$$

$$Ex = m \cdot c_p \left(T_0 - T - T_0 \ln \frac{T_0}{T}\right) dT \qquad (2.17)$$

Further explanation

In a more intuitive way the exergy content of thermal energy of matter can be explained as follows: When matter is cooled down from T to T_0 the heat is first available at T. When the temperature of the matter decreases the heat available has an ever lower temperature according to equation 2.16). Theoretically there could be many Carnot engines attached to this heat flow, each working at dT closer to the reference temperature T . This means the exergy (or maximum work obtainable) changes for each imaginary Carnot engine. This is illustrated in the figure below. Equations 2.16 and 2.17 are both valid for thermal exergy in an amount of matter in a closed system, as well as for a mass flow per unit time in a control volume (open system). Both types of systems are shown in Figure 2.8.

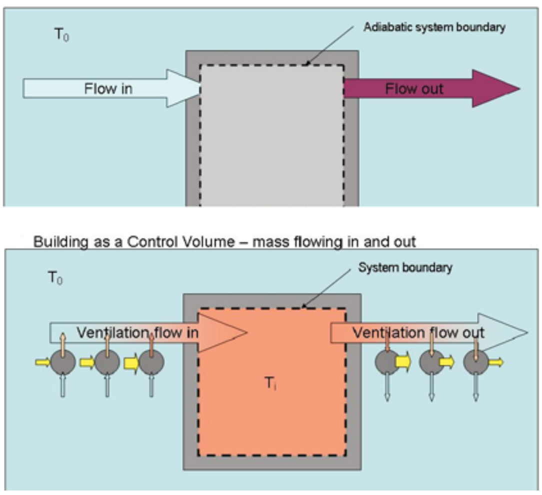


Figure 2.8: Closed system (upper figure) with incoming and outgoing heat flows, but without mass transfer to the environment; the open system in the lower diagram has mass flow going in and out of the system.

2.1.7.1 Comparing the quality factor of heat and matter (thermal exergy)

The quality factor of the thermal energy of matter (surplus or lack of it) is accordingly calculated using the following equation:

$$F_{Q,matter} = \left|1 - \frac{T_0}{(T - T_0)} \ln \frac{T}{T_0}\right| \qquad (2.18)$$

The quality factor of heat as shown in equation 2.6 and the "quality factor" of the thermal energy of matter as calculated with equation 2.18 are plotted in the following Figure for an environmental temperature of 25°C (298 K). This graph has already been shown by Wall and Gong (2001). For this graph the exergy factor between absolute brackets is depicted, always represented as a positive value, in order to simplify the comparison of the lack of thermal energy (cold) and the surplus of thermal energy (warm).

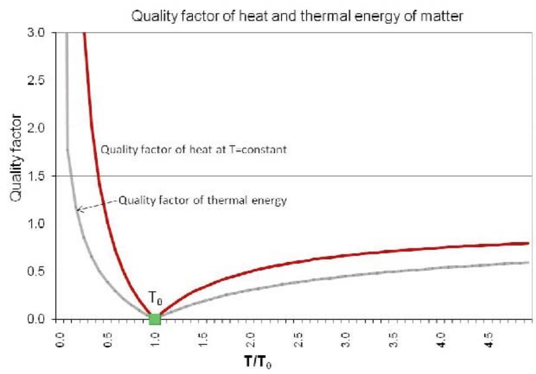


Figure 2.9: Graph showing the quality factor (between absolute brackets) of heat at T and of the thermal energy of matter at T.

The graph also shows the difference between the quality factor of heat at a constant T, and the quality factor of the thermal energy in matter at the same temperature T. It demonstrates that 10 kJ of heat transfer at 100°C has more work potential than 10 kJ of thermal energy in for example water at 100°C ($m \cdot c_p \cdot dT$).

2.1.7.2 The exergy change from T_1 to T_2

The exergy change due to change of thermal (sensible) energy in matter from T_1 to T_2 can be calculated using equation 2.19. The smaller the temperature difference between T_1 and T_2, the closer the quality factor (i.e. expression in parenthesis in equation 2.20) comes to the quality factor of heat using either one of the temperatures,

since $\ln\frac{T_2}{T_1} \approx \left(\frac{T_2}{T_1} - 1\right)$ as $\frac{T_2}{T_1} \longrightarrow 1$

$$Ex = m \cdot c\left(T_2 - T_1 - T_0 \cdot \ln\frac{T_2}{T_1}\right) \quad (2.19)$$

$$Ex = Q \cdot \left(1 - \frac{T_0}{T_2 - T_1} \cdot \ln\frac{T_2}{T_1}\right) \quad (2.20)$$

2.1.8 Exergy balance of a building as a control volume

The exergy balance has already been introduced in the ECBCS Annex 37 guidebook (Ala-Juusela 2003). In this work the exergy balance of a building is discussed in detail, regarding the building as a control volume (which means there is transfer of heat and matter across the system boundaries).

The general exergy balance can be written as follows:

$$Ex_{in} + Ex_{out} - Ex_{sto} - Ex_{irrev} = 0 \quad (2.21)$$

(adapted from (Shukuya and Hammache, 2002); It is noted that Ex_{out} is considered as a negative value since it is a transfer out of the system).

Assuming no work is produced by the building, equation 2.22. (Bejan, 1996) can be used. The first item of the equation represents the total exergy gains from heat transfer, the second and third items together represent the exergy gains from the transfer of matter (ingoing minus outgoing) and the last item refers to the exergy destroyed within the system, i.e. thermal zone of the building.

$$\Delta Ex_{sto} = \sum_j \left(1 - \frac{T_0}{T_j}\right) Q_j + \left(\sum_i m_{in,i} \cdot e_{in,i} - \sum_e m_{out,e} \cdot e_{out,e}\right) - Ex_{irrev} \quad (2.22)$$

Where:

ΔEx_{sto}	The exergy stored, i.e. exergy increase of the system (or decrease in case of a negative value).
$\sum_j \left(1 - \frac{T_0}{T_j}\right) Q_j$	Sum of exergy transfer accompanying all heat transfer across the boundaries at T_j. In this factor all heat flows are summarized. This means that a heat flow **out of** the system will have to be regarded as a negative heat flow).
$\left(\sum_i m_{in,i} \cdot e_{in,i} - \sum_e m_{out,e} \cdot e_{out,e}\right)$	The sum of the exergy content of all ingoing matter minus the sum of the exergy content of all outgoing matter. When regarding only the thermal component of the exergy this can be calculated using equation 2.19.
Ex_{irrev}	Exergy destruction due to thermodynamic irreversibilities within the zone. The destruction of exergy can take place due to mixing of heat flows and matter at different temperatures.

This is the general exergy balance for a control volume. It will be applied to a building in section 2.3.2.

2.2 Description of the method for exergy analysis

2.2.1 Input-output approach

In order to improve the energy and exergy performance of energy supply in buildings, the whole energy supply chain needs to be assessed. This approach can also be found in new energy regulations and standards (DIN 4701-10, 2003; EnEV, 2009; DIN 18599, 2007, CEN EN 13790:2004). For this the energy supply chain in buildings is divided into several subsystems. Figure 2.10 shows the subsystems, from primary energy conversion to the building envelope, of such an energy supply chain for the particular case of space heating applications.

For assessing the energy performance of the complete energy chain, usually a simplified input/output approach is followed. A similar approach can be used for exergy analysis. This whole exergy chain analysis is implemented in an Excel based predesign tool developed by Schmidt (2004) in the framework of the ECBCS Annex 37 program. The tool has been improved and enhanced within the frame of the Annex 49 project.

The input-output approach followed in the MS Excel-based pre-design tool for a steady-state assessment can also be applied for dynamic analysis. Equations for a dynamic analysis based on this input-output schema are shown in detail in section 1.2 for each of the subsystems in Figure 2.10.

All conversion steps in the energy supply chain are directly related to each other and their performance often depends on one another. Analysis of single components happens as part of the energy supply chain, but furthermore, an overall optimization of the whole building energy systems can be accomplished. Optimization of single components is desirable and required, but the influence of optimising one component on the performance of the following and previous ones should always be regarded (Torío et al., 2009). With the holistic energy and exergy analysis of the whole supply chain implemented on the MS Excel tool, optimization of single components which might have a negative influence on other steps of the energy supply process is avoided.

The models for exergy assessment presented here follow the sign convention mentioned above, i.e. exergy inputs are regarded as positive and exergy outputs are regarded as negative.

2.2.1.1 Steady-state, quasi-steady state and dynamic approaches

Steady-state and quasi-steady state estimations of the energy demands and flows in buildings are proposed and used by building regulations in several European countries (EnEV, 2009; EN 13790, 2008). However, exergy is a parameter that refers to both the state of the reference environment and that of the system under analysis. As stated in section 2.1.2 for dynamic exergy analysis of building systems here outdoor air is considered as reference environment. Exergy flows have shown to be very sensitive to variations of the chosen reference conditions when the variables of the system and those of the environment do not differ very much from each other, which is the case of space heating and cooling in the built environment. Thus, an estimation of the error of steady-state exergy assessment as compared to dynamic approaches is mandatory. In this section, results found in the literature comparing both evaluation methods are presented.

Alternatively a quasi-steady state assessment can be performed. Quasi-steady state represents a hybrid between fully dynamic and fully steady-state calculation methods. The exergy flows are evaluated following a steady-state approach, i.e. storage pheno-

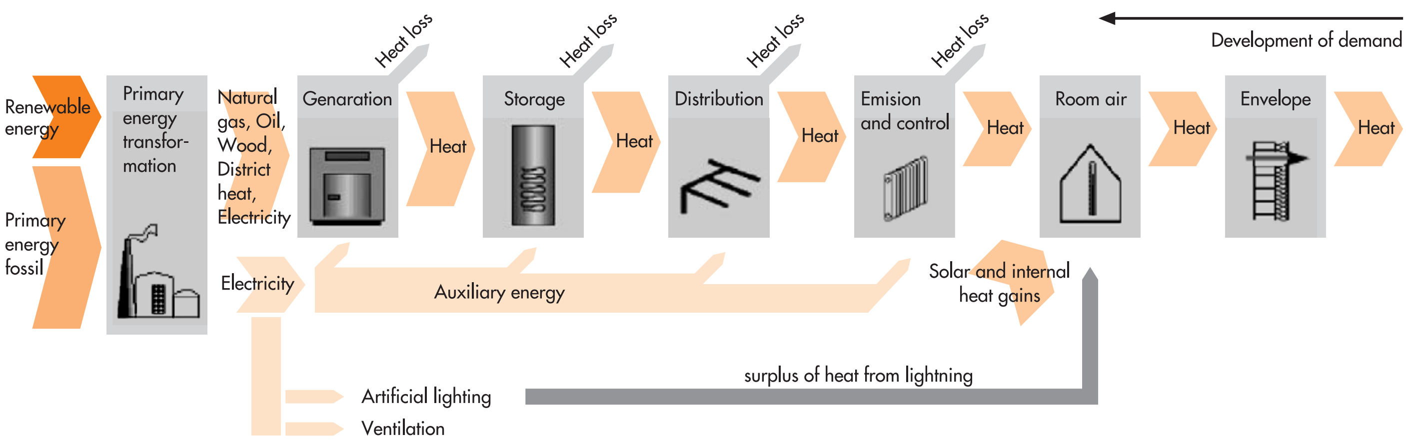


Figure 2.10: Energy supply chain for space heating in buildings, from primary energy transformation to final energy, including all intermediate steps up to the supply of the building demand (Schmidt, 2004).

mena are disregarded, over discrete time-steps. Energy flows, in turn, are modelled dynamically. This simplified quasi-steady state evaluation method is also compared by means of two building case studies to a fully dynamic approach.

2.2.1.2 Steady-state vs. quasi-steady state approach
Angelotti and Caputo (2007) evaluate the difference between steady state and quasi-steady state analysis for heating and cooling systems in two representative Italian climates, namely Milano and Palermo. Here, only thermal exergy flows are regarded, i.e. the reference and indoor environments are only defined based on their temperature levels and no considerations on air humidity are included. For the quasi-steady state assessment a timestep of 1 hour is chosen.

Two different building systems are chosen for comparison: a reversible air-source heat pump (i) and a condensing boiler coupled with direct ground cooling (ii). Steady state exergy analysis is performed using design conditions (i.e. design outdoor temperature) and mean monthly outdoor temperatures for the coldest (January) and warmest (July) months. The coefficients of performance (COP) of the building systems for steady state analysis are taken accordingly to the outdoor temperature regarded in each case. Quasi-steady state and steady state exergy efficiencies are compared. Equation 2.23 shows the expression for the steady state exergy efficiency for the heat pump. The variable COP in equation 2.23 can be the energy efficiency of the heat pump under design conditions or the average performance over the heating period. Similarly, T_0 can be the design outdoor air temperature the average outdoor air temperature over the heating season. Steady-state results corresponding to design conditions and average conditions for January are presented in Table 2.1. Room air temperature T_r is assumed as constant 293 K in both cases.

$$\Psi_{\text{steady}} = COP\left(1-\frac{T_0}{T_r}\right) \qquad (2.23)$$

Quasi-steady state exergy efficiencies can be presented in terms of average values of the exergy efficiency for each time step $\Psi_{\text{q-steady,avg}}$ (equation 2.24), or in terms integral efficiencies obtained as the total exergy demand of the building over the month divided by the total exergy consumption of the system in the same month $\Psi_{\text{q-steady,intg}}$ (equation 2.25 for the same system).

Instantaneous exergy efficiencies $\Psi_{\text{q-steady,avg}}(t_k)$ in equation 2.24 are calculated as a function of the energy efficiency over the hour $COP(t_k)$ and the instantaneous values of the outdoor air T_0 (t_k) and indoor air temperatures $T_r(t_k)$ for the given hour. N represents the number of hours for the evaluation period regarded.

$$\Psi_{\text{q-steady,avg}} = \overline{\Psi_{\text{q-steady}}(t_k)} = \frac{1}{N}\sum_{k=1}^{k=N} COP\,(t_k)\left(1-\frac{T_0(t_k)}{T_r(t_k)}\right) \qquad (2.24)$$

$$\Psi_{\text{q-steady,intg}} = \frac{\sum_{k=1}^{N} Q_{dem}(t_k)\left(1-\frac{T_0(t_k)}{T_r(t_k)}\right)}{\sum_{k=1}^{N} W(t_k)} \qquad (2.25)$$

Main results for the case of Milan are shown in Table 2.1 Results form the paper (Angelotti and Caputo, 2007) have been complemented here with values for the quasi-steady state seasonal exergy efficiency $\Psi_{\text{q-steady,intg}}$.

Steady state exergy efficiencies for the heating case using average outdoor temperatures are very close to those resulting from dynamic exergy analysis. However, for the cooling case mean monthly outdoor temperature is below indoor design temperature, and no exergy analysis could be performed. In turn, using design values for the estimation of the exergy efficiency leads to great mismatching as compared to quasi-steady state analysis: differences of up to 42% are found. The authors remark that the difference is larger for cooling rather than heating systems and for Palermo rather than Milan, i.e. the more the quality factor in equations 2.23 and 2.24 is sensitive to outdoor temperature variations. Figure 2.11 shows the greater relative variations experimented by the quality factor for summer than for winter conditions.

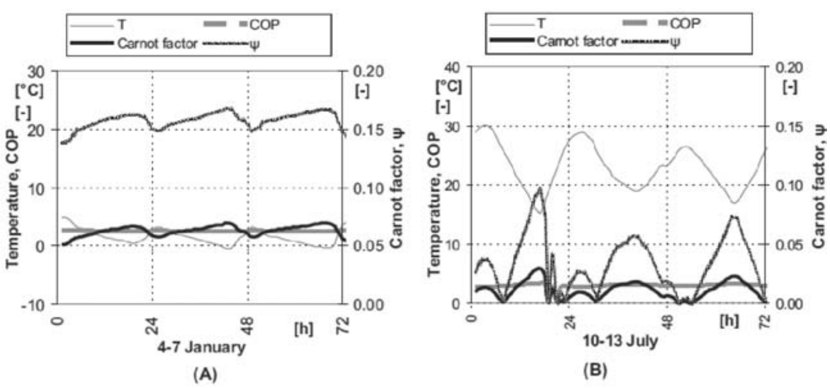


Figure 2.11: Dynamic variation of the outdoor temperature (taken as reference T_0, quality factor and exergy efficiencies for heating and cooling conditions in Milan.

Table 2.1: Comparison of exergy efficiencies for a reversible air source heat pump (i) and a condensing boiler coupled with direct ground cooling (ii) for January and July (in %) in Milan (Angelotti and Caputo, 2007).*

**Here reversible means that the heat pump can be used for heating and cooling purposes by reverting the thermodynamic cycle.*

Conditions	System	Exergy Efficiency (%)	
		January	July
Steady state design conditions Ψ_{steady}	(i) (ii)	18.4 7.9	5.2 20.1
Steady state monthly averages Ψ_{steady}	(i) (ii)	15.7 6.1	- -
Quasi-steady state monthly analysis, average approach $\Psi_{q\text{-}steady,avg}$	(i) (ii)	15.7 6.2	- -
Quasi-steady state monthly analysis, seasonal approach $\Psi_{q\text{-}steady,intg}$	(i) (ii)	16.2 6.5	- -

In a more recent study by the same authors (Angelotti and Caputo 2009), the comparison between steady state and quasi-steady state analysis has been extended to the whole season. The good agreement between the two methods, when a monthly average outdoor temperature is adopted for the steady state case, is limited to the months in which the heating system is on most of the time or the building energy demand is high. On the contrary in the months in which the system is on for a small fraction of the time, a significant mismatch can be expected between the two methods. Consequently on a seasonal basis, including full demand and low demand months, the discrepancy can be relevant.

It is remarkable that despite higher COP for the heat pump is achieved in summer 3.40, exergy efficiencies are significantly lower for the cooling case (around 0.05 and 0.15 for the cooling and heating cases, respectively). This rises from the fact that required indoor temperature under cooling conditions is very close to outdoor air temperature and in consequence, exergy demand for space cooling purposes is extremely low. Therefore, cooling processes will always have intrinsically low exergy efficiency unless they are supplied with environmental heat. Subsequently, there is a strong necessity of reducing cooling loads as much as possible and supply the coolness to meet the required cooling loads by passive means whenever possible.

These results are coherent with findings from Sakulpipatsin (2008), who points out that mismatching between steady-state and dynamic yearly analysis for cold or mild climates are lower than 10%.

Thus, it can be concluded 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. Yet, exergy flows in cooling applications can only be assessed by means of dynamic analysis, where variations in outdoor reference conditions are taken into account (Torío et al., 2009).

The impact of variable climatic conditions is expected to be different in different energy systems. For example, the exergy input and exergy losses of a condensing boiler are expected to be rather constant even under varying outdoor reference conditions, since high quality fossil fuels with a constant quality factor or 0.94 is being used. In turn, the temperature of the heat output from a solar thermal system or a ground source heat pump (GSHP) varies significantly depending on outdoor conditions. Thus, strong variations in the quality factor associated to the exergy flow from the solar thermal[6] and GSHP systems are expected and big mismatching between stationary and dynamic exergy analysis can be presumed. Therefore, if the goal of exergy analysis is to compare different energy systems, dynamic exergy analysis are preferable, so that errors arising from the steady state assessment can be excluded and the differences between energy systems can be solely attributed to improved or optimized performance.

2.2.1.3 Quasi steady-state vs. dynamic approach

In this section, equations for a quasi-steady state and dynamic approaches for exergy analysis are presented. In order to better understand and clearly explain the differences between both approaches an example of the exergy balance of the subsystem "room-air"[7] (see Figure 2.12) as an energy system within a building is presented.

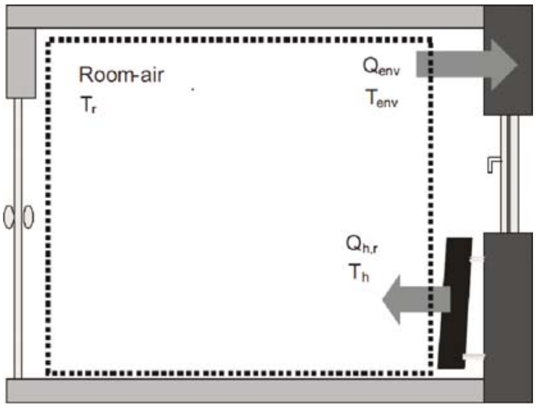


Figure 2.12: Room-air in a building as an example to show the difference between dynamic and quasi-steady state approaches for exergy analysis.

Dynamic approach

A dynamic exergy analysis implies the assessment of all storage processes within the energy systems regarded. Equation 2.26 is the general expression for a dynamic exergy analysis of the "room-air" subsystem. Such an analysis requires a high level of detail and complex equations. Irreversibilities in equation 2.26 refer to the unavoidable losses in the potential of the energy flow arising from the temperature difference between the surface of the radiator T_h and the room air temperature T_r, which is the driving force for the heat transfer.

$$Ex_{in}(t) = Q_{h,r}(t_k)\left(1-\frac{T_0(t_k)}{T_h(t_k)}\right) \quad (2.27)$$

$$Ex_{iout}(t) = Q_{env}(t_k)\left(1-\frac{T_0(t_k)}{T_{env}(t_k)}\right) \quad (2.28)$$

$$Ex_{sto,r}(t) = m_r c_{p,a}\left[\left(T_r(t_k)-T_r(t_{k-1})\right)-T_0(t_k)\ln\frac{T_r(t_k)}{T_r(t_{k-1})}\right] \quad (2.29)$$

$$Ex_{irrev}(t_k) = T_0(t_k)S_{gen}(t_k) \quad (2.30)$$

The equations presented here can be applied to every timestep assumed for a dynamic energy simulation, represented by $t_k - t_{k-1}$ in the equations.

Alternatively, a quasi-steady state approach for exergy analysis combined with dynamic energy simulations could be applied. In a quasi-steady state methodology, exergy flows are evaluated assuming steady state conditions for every small timestep assumed for the dynamic energy simulation. Exergy analysis can be performed, thus, with relatively simple equations using the results from dynamic energy calculations (i.e. temperature, energy and mass flows) as input.

Quasi-steady state approach

The general expression for calculating the exergy losses for the "room-air" subsystem following a quasi-steady state approach is shown in equation 2.31.

The main difference between a dynamic and quasi-steady state approach for exergy analysis is that in the latest storage phenomena are neglected and, thus, not analysed separately but implicitly in the irreversibilities.

$$\begin{aligned}(\text{exergy consumed})_{dyn} &= (\text{exergy input}) + (\text{exergy output}) - (\text{exergy stored in the room-air})\\ &= (\text{Irreversibilities})\end{aligned} \quad (2.26)$$

According to the heat flows and temperatures shown in Figure 2.12 the exergy input, output and stored in the room-air and the irreversibilities can be calculated as shown in equations 2.27, 2.28, 2.29 and 2.30 respectively. Tenv in equation 2.28 is the inside surface temperature of the walls in the building envelope.

On the contrary, in a dynamic approach exergy consumption would only be due to irreversibilities and entropy generated and exergy stored would be regarded separately as a further term (input or output) in the exergy balance (see equations 2.32 and 2.33)[8].

$$\begin{aligned}(\text{exergy consumed})_{q\text{-steady}} &= (\text{exergy input}) + (\text{exergy output})\\ &= (\text{Irreversibilities, including exergy stored in the room air})\end{aligned} \quad (2.31)$$

$$Ex_{cons,q-steady}(t) = Q_{h,r}(t_k)\left(1-\frac{T_0(t_k)}{T_H(t_k)}\right)+Q_{env}(t_k)\left(1-\frac{T_0(t_k)}{T_{env}(t_k)}\right) \quad (2.32)$$

$$Ex_{cons,dyn}(t_k) = Ex_{Irrev}(t_k) = Q_{h,r}(t_k)\left(1-\frac{T_0(t_k)}{T_H(t_k)}\right)-m_r c_{p,a}\left[\left(T_r(t_k)-T_r(t-1)\right)-T_0(t)\ln\frac{T_r(t_k)}{T_r(t_{k-1})}\right] + Q_{env}(t_k)\left(1-\frac{T_0(t_k)}{T_{env}(t_k)}\right) \quad (2.33)$$

Case studies:

Room-air

To show the disagreement between quasi-steady state and dynamic approaches a case study has been dynamically simulated in dynamic energy simulation environment TRNSYS. Equations for a dynamic 2.33 and quasi-steady state 2.32 assessments of the exergy losses in the room-air of the building have been implemented in the model. For the dynamic analysis, the energy stored in the room-air has been evaluated as a function of its dynamic temperature change (Tr(t $_k$)-Tr(t $_{k-1}$)) following equation 2.33. For the quasi-steady state approach, the exergy of energy stored is not included in the balance (equation 2.32). A three storey multi-family dwelling simulated as one thermal zone for each storey has been taken as a case study. Night setback is considered from 23 h to 5 h, with a lower limit for the room air temperature is 16°C. It has been assumed that the net transmission losses to the outdoor Qenv happen at the indoor air temperature (i.e T_{env} =T_r in Figure 2.13) and the active heat input Qh and net heat output from the zone Q_{env} (which with the adopted sign convention has a negative value if it is an output) equal the energy stored in the room air $Q_{sto,r}$ (equation 2.34).

$$Q_{h,r}(t_k)+Q_{env}(t_k)=Q_{sto,r}(t_k) \quad (2.34)$$

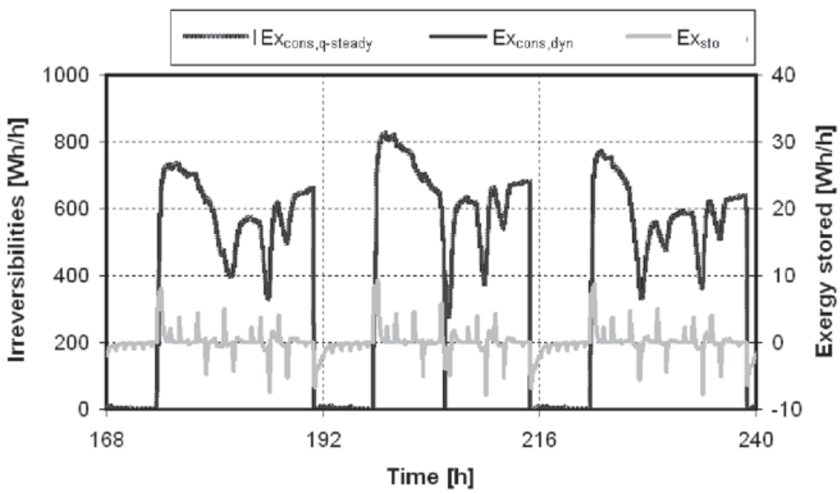


Figure 2.13: Dynamic behaviour of the exergy stored in the room air (right Y-axis, "Ex$_{sto}$") and the irreversibilities following quasi-steady ("Ex$_{cons,q\text{-}steady}$") and dynamic ("Ex$_{cons,dyn}$") approaches (left Y-axis).

In Figure 2.13 the good agreement on the dynamic behaviour of the exergy losses using both approaches is graphically shown. Exergy stored in the room air is very small, as it is in energy terms due to the low specific heat capacity of air. Mismatching on a monthly balance for January conditions is 0.006%. The net exergy stored in the wall over one month represents 0.0021% of the exergy input into the room-air from the emission system, being thus negligible. Exergy stored in each timestep represents usually less than 0.1% of the exergy input into the room air.

Storage is a periodic phenomenon, getting stored and released depending on the surrounding conditions. To avoid the influence of cancelling out exergy stored and released over a long period of time (such as one month) the exergy stored as compared to the exergy input and the exergy consumed regarding storage (i.e. dynamic approach) and disregarding it (quasi-steady state approach) are compared on a 12 hour basis. The period between 168 h and 180 h is regarded, where the first part corresponds to night setback operation (168-173h). For this period of time, the exergy stored represents 0.03% of the exergy input in the room air, and the exergy consumed following a dynamic approach is only 0.088% lower than that estimated following a quasi-steady state approach.

Following it can be concluded that a quasi-steady state approach for systems without great storage capacity is suitable.

Analytical justification of quasi-steady state approach

The exergy terms involved in the exergy balance equation for the room air are $Ex_{in,r}$ (equation 2.35), $Ex_{out,r}$ (equation 2.36), $Ex_{sto,r}$ (equation 2.37). The latter may be easily rewritten as:

$$Ex_{in,r}(t) = Q_{h,r}(t_k)\left(1 - \frac{T_0(t_k)}{T_h(t_k)}\right) \qquad (2.35)$$

$$Ex_{out,r}(t) = Q_{env}(t_k)\left(1 - \frac{T_0(t_k)}{T_{env}(t_k)}\right) \qquad (2.36)$$

$$Ex_{sto,r}(t_k) = m_r c_{p,a}\left[\left(T_r(t_k) - T_r(t_{k-1})\right) - T_0(t_k)\ln\frac{T_r(t_k)}{T_r(t_{k-1})}\right] = E_{sto,r}(t_k)\left[1 - \frac{T_0(t_k)\ln\frac{T_r(t_k)}{T_r(t_{k-1})}}{\left(T_r(t_k) - T_r(t_{k-1})\right)}\right] \qquad (2.37)$$

Let's call $\left(T_r(t_k) - T_r(t_{k-1})\right) = \Delta T_r(t_k)$ and assume that $\frac{\Delta T_r(t_k)}{T_r(t_{k-1})} << 1$

Then:

$$Ex_{sto,r}(t_k) = E_{sto,r}(t_k)\left[1 - \frac{T_0(t_k)}{\Delta T_r(t_k)}\ln\left(1 + \frac{\Delta T_r(t_k)}{T_r(t_{k-1})}\right)\right] \cong E_{sto,r}(t_k)\left[1 - \frac{T_0(t_k)}{\Delta T_r(t_k)}\frac{\Delta T_r(t_k)}{T_r(t_{k-1})}\right] = E_{sto,r}(t_k)\left[1 - \frac{T_0(t_k)}{T_r(t_{k-1})}\right] \qquad (2.38)$$

Let's suppose that from an energy point of view the quasi-steady state approach is a valid approximation, that is:

$$E_{sto,r}(t_k) << Q_{env}(t_k), Q_{h,r}(t_k) \qquad (2.39)$$

Then, if we also assume that the involved temperatures T_h, T_{env} and T_r are similar, in the sense that he corresponding Carnot factors are similar too:

$$\left(1 - \frac{T_0(t_k)}{T_h(t_k)}\right) \approx \left(1 - \frac{T_0(t_k)}{T_{env}(t_k)}\right) \approx \left(1 - \frac{T_0(t_k)}{T_r(t_k)}\right) \qquad (2.40)$$

we can easily find that:

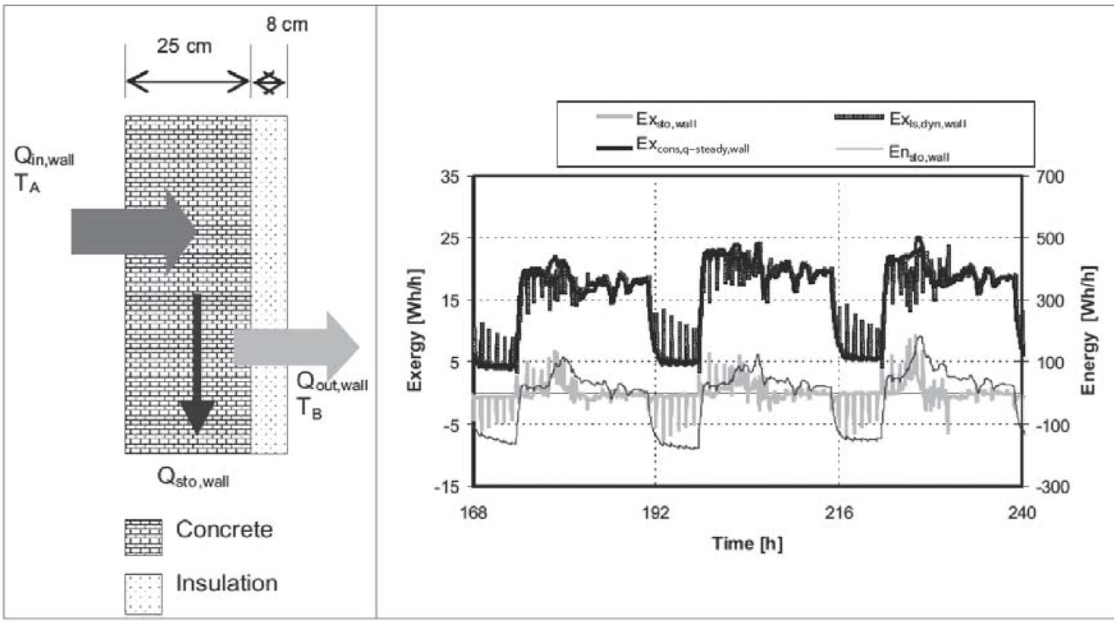
$$Ex_{sto,r}(t_k) = E_{sto,r}(t_k)\left[1 - \frac{T_0(t_k)}{T_r(t_{k-1})}\right] << Ex_{in,r}(t_k), Ex_{out,r}(t_k) \qquad (2.41)$$

Therefore the quasi-steady state approach is a valid approximation also from the exergy point of view.

Building wall

Building walls have a much bigger storage capacity than room-air. To check the influence of a quasi-steady assessment on such a building element, a massive wall of the multi-family dwelling has been taken as a case study. In Figure 2.14 (b) results from both approaches can be found for the wall case study shown in Figure 2.14 (a).

Energy stored in the wall can be calculated from the energy balances for the wall in TRNSYS (equation 2.42). Energy inputs and outputs of the wall include convective, conductive and radiative energy inputs in the wall. As shown in equation 2.43, to evaluate the exergy of the energy stored in the wall, the temperatures of each wall layer (I index in the equation)



(a) (b)

Figure 2.14: (a):Case study of an east facing wall of a building to show the difference between dynamic and quasi-steady state approaches for exergy analysis.
(b):Dynamic behaviour of the exergy stored in a building wall facing east and the irreversibilities following quasi-steady ("$Ex_{cons,q-steady,wall}$") and dynamic ("$Ex_{ls,dyn,wall}$") approaches. The exergy stored ("$Ex_{sto,wall}$") in the wall and the energy stored ("$En_{sto,wall}$") are also shown.

Exergy stored, "$Ex_{sto,wall}$", and exergy losses without accounting the stored exergy as a loss ("$Ex_{cons,dyn}$", equation 2.43) correspond to the dynamic approach. Exergy losses in the quasi-steady assessment are represented by the curve "$Ex_{cons,q-steady}$" (equation 2.44). For completeness, energy stored in the wall is also shown in Figure 2.14 (b).

is needed. However, a discretization of the wall to obtain the temperature in different layers inside the wall is not directly possible in the TRNSYS model used since it uses the Transfer Functions Method is used to model heat transfer in the wall (TRNSYS, 2006). Therefore, as simplification it has been assumed that the temperature of the wall in each time

$$Q_{in,wall}(t_k) + Q_{out,wall}(t_k) = Q_{sto,wall}(t_k) \qquad (2.42)$$

$$Ex_{cons,dyn}(t_k) = Q_{in,wall}(t_k)\left(1-\frac{T_0(t_k)}{T_A(t_k)}\right) - \sum_{i=1}^{i=n} m_i c_{p,i}\left[\left(T_{i,wall}(t_k) - T_{i,wall}(t_{k-1})\right) - T_0(t)\ln\frac{T_{i,wall}(t_k)}{T_{i,wall}(t_{k-1})}\right] + Q_{out,wall}(t_k)\left(1-\frac{T_0(t_k)}{T_B(t_k)}\right) \qquad (2.43)$$

$$Ex_{cons,q-steady}(t_k) = Q_{in,wall}(t_k)\left(1-\frac{T_0(t_k)}{T_A(t_k)}\right) + Q_{out,wall}(t)\left(1-\frac{T_0(t_k)}{T_B(t_k)}\right) \qquad (2.44)$$

Energy stored in the wall can be calculated from the energy balances for the wall in TRNSYS (equation 2.42). Energy inputs and outputs of the wall include convective, conductive and radiative energy inputs in the wall. As shown in equation 2.43, to evaluate the exergy of the energy stored in the wall, the temperatures of each wall layer (I index in the equation) is needed. However, a discretization of the wall to obtain the temperature in different layers inside the wall is not directly possible in the TRNSYS model used since it uses the Transfer Functions Method is used to model heat transfer in the wall (TRNSYS, 2006). Therefore, as simplification it has been assumed that the temperature of the wall in each timestep is the mean temperature between the inside and outside surface temperatures (T_A and T_B, respectively). Peaks in the dynamic approach are due to the strong influence of a temperature variation inside the wall, as a result of the storage phenomena.

Despite the simplification, good agreement can be found on the behaviour of the exergy losses in both approaches. Mismatching on a monthly balance (January) for the exergy losses is 0.32%. The net exergy stored in the wall over one month represents 0.34% of the exergy input into the wall, being about one hundred times bigger than for the case of "room-air" (see the previous case study). Exergy stored in each timestep represents a very different share of the exergy input into the wall, with values varying between 1% and 160% depending on the dynamic processes involved in the energy storage and release.

To avoid the influence of cancelling out exergy stored and released over a long period of time (such as one month) the exergy stored as compared to the exergy input and the exergy consumed regarding storage (i.e. dynamic approach) and disregarding it (quasi-steady state approach) are compared on a 12 hour basis. For the period of time between 168 h and 180 h, the exergy stored represents 0.84% of the exergy input in the room air, and the exergy consumed following a dynamic approach is only 0.85% lower than that estimated following a quasi-steady state approach. For the period of time between 180 h and 192 h, the exergy stored represents 2.37% of the exergy input in the room air, and the exergy consumed following a dynamic approach is only 2.38% lower than that estimated following a quasi-steady state approach.

Thus, if the main aim of exergy analysis is to improve, study or optimize a building construction, i.e. the storage system taken as case study in this section, the dynamic behaviour of the exergy stored and consumed needs to be analyzed dynamically. A quasi-steady state approach is not accurate enough as to depict the dynamic behaviour of the exergy flows accurately. However, if the aim is to perform exergy analysis on a system level, the dynamic behaviour might not be that relevant, but total required input over a certain period of time might be enough. A quasi-steady state exergy assessment methods combined with dynamic energy analysis (including storage phenomena) is suitable in this case.

Alternatively, for exergy analysis of building systems a further simplification can be done: the exergy input into the building wall can be completely regarded as exergy consumed (Schmidt, 2004), since Ex,out,wall at T_B is finally destroyed when it has become T_0 and thus has no exergy associated (equation 2.45). This simplification would lead to a mismatch of 0.875% on a monthly basis as compared to the fully dynamic approach.

$$Ex_{cons,q-steady}(t_k) = Q_{in,wall}(t_k)\left(1 - \frac{T_0(t_k)}{T_A(t_k)}\right) \qquad (2.45)$$

2.2.2 Exergy demand & detailed exergy flows of the building

Since buildings are fairly complex systems a separate paragraph is devoted to the calculation exergy demand of a building and the exergy of the different flows of heat and matter into and out of the building. In section 2.2.2.1 the definition of the exergy demand is developed, followed by the description of system boundaries for the building. In section 2.2.2.3 a recapitulation of the energy balance equations and energy demand calculation is presented, which are used for the exergy demand calculation. The exergy demand cannot be calculated from an exergy balance since this includes the unknown component of destroyed exergy.

In section 2.2.2.4 the exergy content of cooling demand (heat output) is discussed, showing that there is a difference between cooling at $T_i > T_0$ or $T_i < T_0$.

In section 2.2.2.5 and section 2.2.2.6 a simplified and a detailed exergy demand calculation method are explained and the relevant equations are given. The results of these methods are compared in section 2.2.2.9.

2.2.2.1 Definition of the exergy demand

The energy demand of a building can be defined as the amount of energy required to keep the indoor environment within the comfort ranges required by its users. Similarly, the exergy demand is the amount of exergy required to keep the indoor environment within the comfort ranges required by its users. This is equal to the exergy content of the required energy. In order to achieve a more clarifying description the exergy demand is defined as the minimum amount of work needed to provide the required energy.

Further reflection on the exergy demand

The minimum amount of work depends on the quality of the energy that is required. This means for the minimum amount of work the energy should be provided at the lowest quality possible. In practice however it happens very often that energy is supplied at a higher quality (= more exergy) than necessary, as is the case when heating is supplied at 90 °C to obtain a room temperature of 20 °C. While providing more energy than required would lead to overheating or under-cooling, providing more exergy than required does not lead to overheating or under-cooling; it only leads to the destruction of exergy, since mixing (in this case of higher and lower temperature energy) involves exergy destruction.

Therefore it is important to keep in mind that the ideal exergy demand is the minimum amount of exergy required to provide the required energy at the lowest possible quality. Any surplus of exergy provided to the zone implies exergy destruction between the heating or cooling device and the demand, which will be separately shown in the analysis. This partly unavoidable exergy destruction happens due to the irreversible heat transfer process between the heating or cooling element and the indoor air, due to the temperature difference among them. The destruction will be assigned to a fictive component called "room air", as explained in section 2.3.2.2.

2.2.2.2 System boundaries of the energy demand calculation

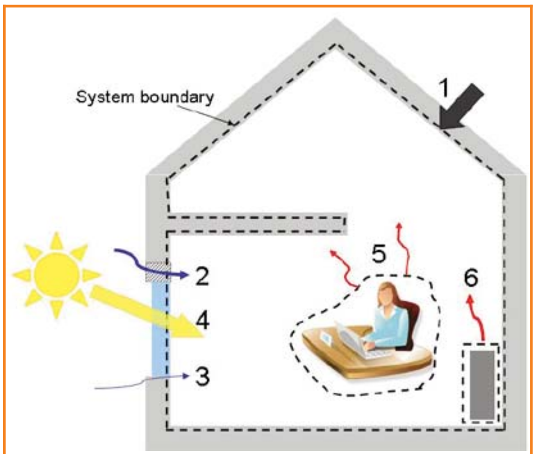
The energy demand is related to the required comfort of the thermal zones of the building. The system boundary of the building zone(s) is taken at the inner surface of all walls, floors and ceilings enveloping the building zone. Also internal walls, floors and ceilings are outside the system boundaries. Energy stored in the building structure is included implicitly in the energy balance, for a net balance of transmission losses and energy stored or released from the building's thermal mass is considered.

Also all active devices (heating, cooling or air handling, including heat recovery) are regarded as outside the boundaries of the thermal zones where thermal comfort needs to be achieved.

The system boundaries as applied in this work are shown in the figure below.

2.2.2.3 Recapitulation of energy balance equations and energy demand calculation

The energy demand of a building can be calculated using energy balance equations. In a building there are different energy flows going into and out of the building zones, depending on the indoor and outdoor conditions, the building characteristics and the user behaviour. In the picture below all the relevant energy flows into and out of the building are shown:



1. Transmission (heat transfer through closed surfaces)*

2. Ventilation (controlled airflow into and out of the building through devices designed for this purpose)

3. Infiltration (uncontrolled airflow into and out of the building, through cracks)

4. Solar heat gains

5. Internal heat gains (lighting, appliances and people)

Active energy input (+ = heating, - = cooling)

*with dynamic simulations this includes heat coming from energy stored in the walls

Figure 2.15: Scheme showing the boundaries of the system "thermal zones of the building" as well as the main energy interactions presented in it.

Since energy is never destroyed, the basic energy balance equation is as follows:

Energy_in + Energy_out – d_Energy =0

(where Energy_out is regarded as a negative value)

The energy change in the system (d_Energy) relates to the energy stored in the air of the thermal zones. The energy stored in the walls is excluded due to the choice of system boundaries. In case of steady state calculations d_Energy is equal to zero.

Solar and internal gains are by definition always gains (energy_in), but the other energy flows can either represent a gain or a loss, depending on the indoor and outdoor temperatures. As described in 2.1.1 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. Then the energy balance for the thermal zone(s) of a building can then be written as follows.

$$Q_{trans} + E_{th,inf} + E_{th,vent} + Q_{int} + Q_{sol} + Q_{dem} - d_{Qr} = 0 \quad (2.46)$$

Energy	Definition	Basic equation[9]
Q_{trans}	= energy gains from transmission (*including from stored energy in case of dynamic simulations)	$U \cdot A \cdot (T_0 - T_r)$
$E_{th,vent}$	= energy gains from ventilation	$m \cdot c_p \cdot (T_0 - T_r)$
$E_{th,inf}$	= energy gains from infiltration	$E_{th,\inf} = m \cdot c_p \cdot (T_0 - T_r)$
Q_{int}	= energy gains from internal heat loads	
Q_{sol}	= energy gains from the sun	$Q_{sol,window} = \sum_{orientations} A_{window} \cdot g_i \cdot G_{window}$
Q_{dem}	= active energy input (or output in case of a negative value)	
$dE_{th,syst}$	= the change of energy in the system (the thermal zones)	

In dynamic simulation the energy going into or coming out of the thermal mass of the walls, floors and ceilings is included in Q_{trans}, then representing the total energy flow from the inside of the wall to the inner surface of the wall. This energy flow is a result of the temperature in the walls and the temperature of the inner surface of the wall.

Assuming that indoor air temperature is equal to a chosen set point temperature, equation 2.6 can be used to calculate the sensible energy demand, resulting is a positive value in case of heating, and a negative value in case of cooling. A heating demand means a thermal energy input is required; a cooling demand means a thermal energy output is required.

In Figure 2.16 below the result of a steady state energy balance for three situations for a standardised office space are shown. To be able to compare gains (in) and losses (out) of the office space both are represented as a positive value. The indoor air temperature for the heating case is 20°C (situation 1) and for the cooling case is 25°C (situations 2 and 3).

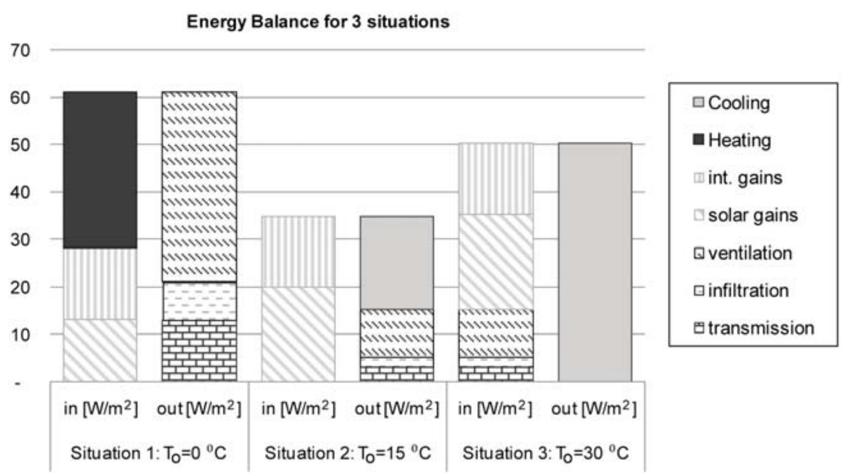


Figure 2.16: Energy balance of a standard office room in three different situations, resulting in heating (situation 1), or cooling (situation 2 and 3).

2.2.2.4 The exergy of cooling demand

As stated in section 2.2.2.3 a heating demand represents a required energy input and a cooling demand represents required energy output. In exergy terms however, a cooling demand can represent a required exergy input or an exergy output, depending on the indoor and outdoor temperatures.

Looking at the 3 situations in Figure 2.16 it can be seen that there are two situations when there is a cooling demand.

In the last case (situation 3) the environmental temperature is higher than the indoor temperature, a cooling demand represents a required exergy input, due to the fact that obtaining or maintaining any state different from the environmental state requires an exergy input, be it warmer (warm exergy) or cooler (cool exergy). This is also explained by Shukuya (2009).

In situation 2 there is a cooling demand even though the environmental temperature is lower than the indoor temperature, which can occur due to high internal and solar gains. In this case the aim is to bring the temperature of the system closer to the environmental temperature. This theoretically means that work could be obtained, meaning there is no exergy demand but theoretically there is exergy available.

Table 2.2: Heating and cooling demand situations

Situation:			Energy	Exergy
1	$T_0 < T_r$	losses > gains	Heating (heat input)	Input/exergy required
2	$T_0 < T_r$	losses < gains	Cooling (heat output)	Output/exergy available
3	$T_0 > T_r$	losses < gains	Cooling (heat output)	Input/exergy required

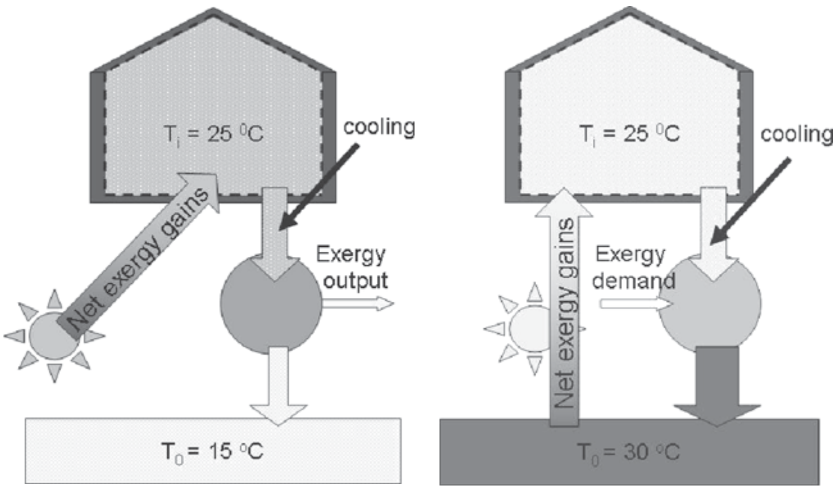


Figure 2.17: Exergy demand related to cooling at $T>T_0$ (left) and $T<T_0$ (right)

Consequently, for an analysis of thermal exergy demand in buildings, three situations can occur as shown in Figure 2.16 and outlined in Table 2.2. The energy balances in this figure are for a standard office room in The Netherlands for these three situations, resulting from different outdoor air temperatures and different solar heat gains.

In the figures below the exergy demand for the two cooling situations are illustrated using an imaginary Carnot engine. In the left figure is can be seen that the transfer of heat from a warmer to a cooler system (the warm room to the cooler environment) could theoretically produce work and thus there is exergy available, in other words there is an amount of unwanted warm exergy in the building. (This is possible since buildings are not built with the aim to have the highest exergy content, but with the aim to provide comfortable thermal conditions).

In the right picture heat has to be transferred from a cooler to a warmer system, which means work is required and the cooling represent an exergy input. (see also section 2.1.5).

It is noted that the exergy demand represents the theoretical minimum amount of exergy required by the thermal zones in order to keep the temperature within the required temperature range. This minimum demand is only related to the subsystem 'building envelope' (see Figure 2.10) and not to the subsystems (e.g. emission and generation) that provide the cooling. These cooling devices of a building often do require exergy independent of the minimum exergy demand (being a real demand or not, as explained above). The calculation of the minimum exergy demand is used in order to quantify the losses between the exergy demand and the exergy supplied by emission system.

In many countries the climate is such that situation 2 ($T>T_0$) happens much more often than situation 3 ($T<T_0$). This means the annual exergy demand for cooling is often really low and it confirms that passive systems should be optimized especially for cooling.

Concluding it can be said that also exergy gives insight in the difference between cooling demand at $T<T_0$ (required cool exergy input) and cooling demand at $T>T_0$ (theoretical warm exergy output).

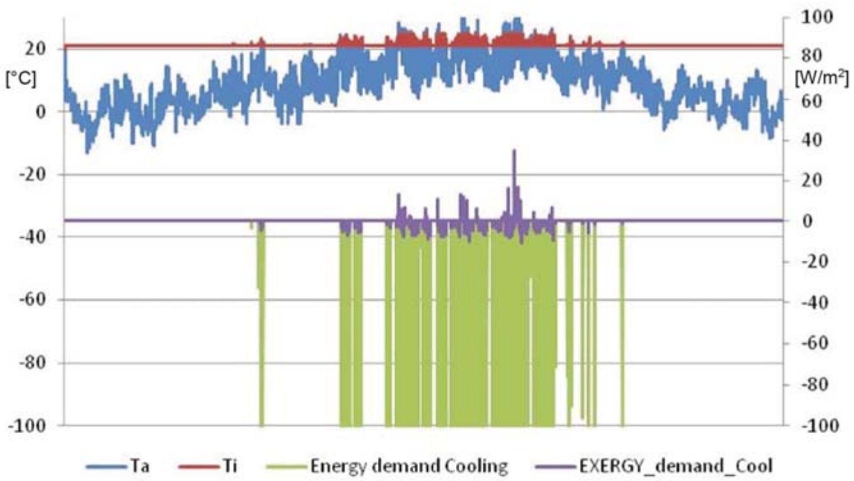


Figure 2.18: Cooling in the Dutch climate: Energy output only requires an exergy input when $T_r<T_0$

2.2.2.5 Simplified Exergy Demand Calculation

From section 2.2.2.4 it becomes clear that the exergy demand cannot be calculated using exergy balance equations. Therefore the exergy demand must be calculated using the results of the energy balance equation. To calculate the exergy demand (defined as the minimum amount of work required to provide the energy demand), the quality of the energy demand has to be determined.

A simplified method to calculate the exergy demand is developed by Schmidt (Schmidt 2004). In this approach it is assumed that the energy demand has the quality of heat (or cold) at the temperature of the thermal zone. This way the exergy demand can be calculated by multiplying the energy demand with the quality factor of heat (or cold) at the indoor temperature, using equation 2.6. This results in equation 2.47 and 2.48 for the calculation of the exergy demand.

$$Ex_{h,simple} = Q_h\left(1-\frac{T_0}{T_r}\right) \qquad (2.47)$$

$$Ex_{c,simple} = Q_c\left(1-\frac{T_0}{T_r}\right) \qquad (2.48)$$

To avoid missing this distinction between the two cooling situations in the analysis, it is recommended to use the equation without absolute brackets (equation 2.7) and regard the cooling demand as a negative value according to the sign conventions as described in section 2.1.1. By doing this the exergy of cooling at $T_r<T_0$ will result in a negative value, indicating there is exergy output (not a required input).

When placing equation 2.6 between absolute brakkets and considering the cooling demand as positive the distinction between the two situations has to be made manually. As stated above, the equation between absolute brackets should therefore be used with care.

T_r is usually considered to be the temperature of the indoor air. However, the mean surface temperature of the surrounding surfaces can be different from the air temperature. Therefore also the operative temperature can be used.

Characteristics of this simplified demand calculation are:

It only takes into account the thermal component of the energy demand; no chemical or pressure components are included. This is reasonable as long as no (de)humidification is present;

The calculation is based on the equation for the exergy accompanying convective heat transfer (equation 2.6). In reality part of the energy demand will be supplied as convective heat and part as radiative heat. Since it is not realistic to create a system with 100% radiative heat, and since the radiative part depends on the emission system used, it is chosen to use the convective equation for the demand calculation. In paragraph 2.3.2.3 (Emission systems) this topic will be further discussed.

The calculation method implies that all the energy is supplied as heat at T_r. This is the limiting temperature at which the energy can be supplied to or removed from the zone ($T\geq T_r$ in case of heating or $T\leq T_r$ in case of cooling). However, it ignores the fact that part of the energy is needed to heat or cool the ventilation air, which can be pre-heated or pre-cooled at a temperature closer to the environmental temperature and whose exergy should be calculated using equation 2.17. In the detailed method the exergy related to ventilation air is calculated separately, and the difference in the results is shown in paragraph 2.2.2.9.

The method described above is a very reasonable approach in many cases, as will be also demonstrated in paragraph 2.2.2.9.

2.2.2.6 Detailed Exergy Demand Calculation

The detailed exergy demand calculation presented in this paragraph is different from the simplified method by differentiating between the exergy demand related to matter (air) and the exergy demand related to heat. Like the simplified method this method does not include humidification and ignores the (small) difference between the exergy convective heat and radiative heat exchange between surfaces with small temperature differences.

As can be seen from Figure 2.15 the total heating demand is a result of different energy 'flows' across the system boundary (heat transfer from transmission and gains and thermal energy related to flows of matter, i.e. air). The total demand covers the compensation of all losses (transmission and storage, ventilation and infiltration) minus the gains. For the energy analysis this results in one net demand for heating, which is partly used to heat the ventilation air (increase the thermal energy of it) and partly used to compensate for transmission (=heat) losses. (The cooling case will be explained later in this paragraph).

As is shown in Figure 2.19 the quality factor of thermal energy of matter at temperature T is smaller than the quality factor of heat at temperature T, which means that less work is ideally required to increase the thermal energy of matter from T_0 to T with a value of e.g. 10 kJ, than to provide 10 kJ of heat at T. Therefore, in order to calculate the ideal exergy demand, meaning the minimum work required to provide the energy demand, it is important to determine which part of the demand can be supplied by increasing the thermal energy of incoming matter, and which part has to be supplied as heat.

To calculate the part of the demand that can be used to heat ventilation air and the part used to compensate for other losses, the heat demand is split into two separate inputs into the building zone:

- an input of preconditioned fresh air;
- an input of heat or cold

A logical approach needs to be followed in order to determine the demand associated with the ingoing ventilation air and the demand associated with heat transfer.

Resulting from the fact that increasing the thermal energy with 10 kJ to T requires less work than producing 10 kJ of heat at T (see Figure 2.9), the logical reasoning is: to calculate the ideal exergy demand, which is the minimum amount of work required to provide the required energy, the exergy demand should be assigned to preheat ventilation air as much as possible and needed, meaning up to a temperature as close to the indoor air temperature as needed but not further. The remaining part of the exergy demand (if present) should be provided as heat at T_r.

This can be further explained in two ways:

Explanation 1:
When assuming the air is entering the building at $T=T_0$, there is mixing of the (colder or warmer) outside air with the indoor air and mixing involves a destruction of exergy. The minimum amount of work needed therefore should be calculated with a minimum occurrence of mixing;

Explanation 2:
From Figure 2.9 it can be seen that the thermal exergy content per unit of energy of warm or cold matter at T is smaller than the exergy content of heat at the same temperature T. (see also explanation in section 2.1.7). Since the ideal exergy demand is the minimum amount of work required to provide the energy at the lowest possible quality, preheating or precooling the outdoor air should be maximized.

From both explanations it can be concluded that the minimum amount of required work is obtained assuming preconditioned ventilation air, with conditions (in our case only temperature) as close to the required indoor air conditions as needed for the energy balance.

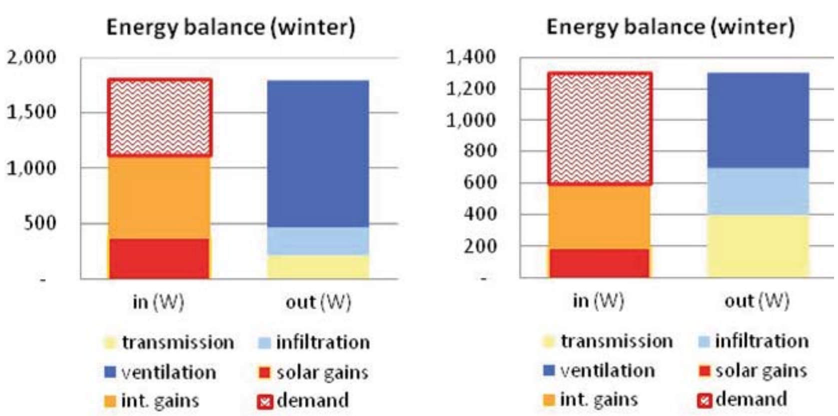


Figure 2.19: Energy balance resulting in total heating demand. (Left: total heating demand < ventilation losses, right: total heating demand > ventilation losses.)

2.2.2.7 Simplified cases to demonstrate the detailed exergy demand calculation

Below four basic cases to demonstrate the detailed exergy demand calculation are shown. In the following the simple and detailed demand calculation results are compared for four more real test cases.

All cases are based on a simple box of 5 x 5 x 5 m, without windows. The characteristics are given below:

T_a (= T_0)	0	°C	= 273 K
T_r	20	°C	= 293 K
A (only vertical surfaces)	100	m^2	
V Volume	125	m^3	
U (average)	0.3	W/m²K	

For readability the two relevant equations for the cases are repeated below:

$$Ex_{dem,h} = Q_{dem,h}\left(1-\frac{T_0}{T_r}\right) \quad (2.49)$$

$$Ex_{dem,vent} = Q_{dem,vent}\left(1-\frac{T_0}{T_{preh}-T_0}\ln\frac{T_{preh}}{T_0}\right) \quad (2.50)$$

Where :
T_r = the indoor air temperature and
T_{preh} = the temperature up to which the ventilation air is preheated

Case 1: No ventilation, no internal heat loads

Energy balance:		
- transmission gains $U\cdot A\cdot(T_0-T_r)$	-600	W
Heating demand	600	W

In this case all the heat is used to compensate for transmission losses (at Tr), thus all the heating has to be supplied as heat at Tr. There is no fresh air intake (ventilation) thus no heat can be supplied to ventilation air.

The exergy demand is therefore: (eq. 2.49)	40.96	W
Exergy factor	6.8	%

Case 2: With ventilation, no internal heat loads

ACH = 2.4 h^{-1} = 0.1 kg/s

Energy balance:		
- transmission gains $(U\cdot A\cdot(T_0-T_r))$	-600	W
- ventilation losses $(m\cdot c_p\cdot(T_0-T_r))$	-2000	W
Heating demand	2600	W

Of this demand a maximum of 2000 W can be supplied to the ventilation air, since then the air will be at temperature T_r. If more heating would be supplied to the ventilation air, T would become higher than T_r, which means the exergy factor will become higher. The remaining 600 W needs to be supplied as heat.

This means the demand is split in two:

Exergy demand to heat ventilation air up to T_r (eq. 2.50)	69.87	W
Exergy demand to supply heat as heat at T_r (eq. 2.49)	40.96	W
Total exergy demand:	110.82	W
Exergy factor of the total:	4.3%	[-]

Case 3: With ventilation, with internal heat loads

ACH = 2.4 h^{-1} = 0.1 kg/s
Internal gains: 20 W/m^2

Energy balance:		
- transmission gains $\left(U \cdot A \cdot \left(T_0 - T_r\right)\right)$	-600	W
- ventilation losses $\left(m \cdot c_p \cdot \left(T_0 - T_r\right)\right)$	-2000	W
- Internal gains:	500	W
Heating demand	2100	W

Of this demand a maximum of 2000 W can be supplied to the ventilation air, since then the air will be at temperature T_r. This means only the remaining 100 W needs to be supplied as heat at T_r. Like in case 2, the exergy demand is split in two:

Exergy demand to heat ventilation air up to T_r (eq. 2.50)	69.87	W
Exergy demand to supply heat as heat at T_r (eq. 2.49)	6.83	W
Total exergy demand:	76.69	W
Exergy factor of the total:	3.7%	[-]

Case 4: With ventilation, with (more) internal heat loads

ACH = 2.4 h^{-1} = 0.1 kg/s
Internal gains: 35 W/m^2

Energy balance:		
- transmission gains $\left(U \cdot A \cdot \left(T_0 - T_r\right)\right)$	-600	W
- ventilation losses $\left(m \cdot c_p \cdot \left(T_0 - T_r\right)\right)$	-2000	W
- Internal gains:	875	W
Heating demand	1725	W

Of this demand a maximum of 1725 W can be supplied to the ventilation air. The resulting indoor air temperature will then be sufficient. This means the air does not need to be preheated up to 20 °C, but up to T_{preh} = 17,25 °C (T_0 + dT of (1725/2000). 20 °C = 17,25 °C), which on a Kelvin Scale is 290.3 K. No additional heat at T_r is required

The exergy demand is therefore:

Exergy demand to heat ventilation air up to T_{preh} (eq. 2.50)	52.31	W
Exergy demand to supply heat as heat	0	W
Total exergy demand:	52.31	W
Exergy factor of the total:	3.0%	[-]

As can be seen from these simplified examples the quality factor of the demand for each case is different, even though the T_0 and T_r are assumed to be equal. Using the simplified exergy demand calculation method all cases will have the same quality factor. The differences are explained for an example that is more representative for true situations in paragraph 2.2.2.9. In the paragraph below the generally applicable equations to calculate the detailed exergy demand are given.

2.2.2.8 Equations for detailed exergy demand calculation

In this paragraph the general equations to be used for real cases (including all energy flows) are given. These equation can also be used as an add on in energy simulation tools, such as TRNSYS.

Like the simplified exergy demand calculation, the detailed calculation cannot be done from an exergy balance either. The detailed calculation therefore will also be based on the energy balance

Equations for the detailed exergy demand calculation – heating case

The energy balance for the heating case can either result in:

(1): total demand < ventilation losses;
(2): total demand ≥ ventilation losses.

The energy needed to heat up the ventilation air is never bigger than either the total demand or the ventilation losses, resulting in equation 2.46. In case 4 the total demand is smaller than the losses related to ventilation the air does not need to be preheated up to T_r and no additional active heat needs to be supplied (the remaining required heat is delivered by (internal) gains). The temperature up to which the air needs to be preheated can be calculated using equation 2.43 and 2.44. With these values for energy and temperature the exergy needed to preheat the ventilation air can be calculated using equation 2.45.

When additional heat is required (Q_{dem} > ventilation losses), the energy and exergy of this additional heat can be calculated using equations 2.47 and 2.48.

It should be noted that the exergy of matter at different conditions is in reality calculated using the enthalpy and the entropy, as explained in 2.1.7. When regarding only the thermal component of the exergy analysis the equations in this paragraph can be used:

Equations for detailed exergy demand calculation of heating demand

(dd stands for detailed demand)

$$Q_{dd,vent,h} = \min(-Q_{vent}, Q_{dem,h;tot}) \quad (2.51)$$

$$\Delta T_{dd,vent,h} = (T_i - T_0) \cdot \frac{Q_{dd,vent,h}}{-Q_{vent}} \quad (2.52)$$

$$T_{dd,vent,h} = T_0 + \Delta T_{dd,vent,h} \quad (2.53)$$

$$Ex_{dd,vent,h} = Q_{dd,vent,h} \left[1 - \frac{T_0}{T_{dd,vent,h} - T_0} \ln\left(\frac{T_{dd,vent,h}}{T_0} \right) \right] \quad (2.54)$$

$$Q_{dd,h} = Q_{dd,tot} - Q_{dd,vent,h} \quad (2.55)$$

$$Ex_{dd,h} = Q_{dd,h} \left(1 - \frac{T_0}{T_r} \right) \quad (2.56)$$

Detailed exergy demand for the cooling case at $T_0 > T_r$

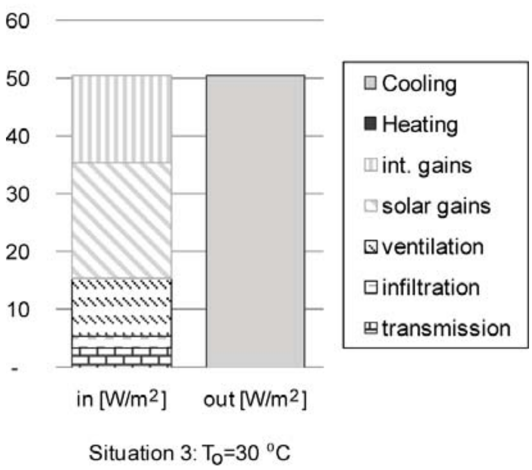


Figure 2.20: Energy balance for a cooling demand situation at $T_0 < T_r$.

For cooling at $T_0 > T_r$ all natural (not active) energy flows represent an unwanted energy gain, as is shown in the energy balance of situation 3 of Figures 2.16 and 2.20 . In this case always the following relation is valid: $Q_c > Q_{vent}$ (where Q_c is regarded as negative). This means the energy needed to pre-cool the ventilation air is equal to the unwanted energy gains from ventilation and the ventilation air always needs to be cooled down until T_r. This results in the following equations:

Equations for detailed exergy demand calculation of cooling demand at $T_0>T_r$

$$Q_{dd,vent,c} = -Q_{vent} \quad (2.57)$$

$$T_{dd,vent,c} = T_r \quad (2.58)$$

$$Ex_{dd,vent,c} = Q_{vent}\left[1 - \frac{T_0}{T_r - T_0}\ln\left(\frac{T_r}{T_0}\right)\right] \quad (2.59)$$

$$Q_{dd,c} = Q_{dem,tot,c} - Q_{vent,c} \quad (2.60)$$

$$Ex_{dd,c} = Q_{dd,c}\left(1 - \frac{T_0}{T_r}\right) \quad (2.61)$$

Detailed exergy demand for the cooling case at $T_0<T_i$

As explained in section 2.2.2.4 the need for cooling (=energy output) at $T_0<T_r$ is not actually an exergy demand, but it is an output of unwanted exergy. This exergy is delivered to the building by (internal) gains, and could be completely "harvested" as heat at T_r. The total exergy "demand" can therefore be calculated using 2.63, which will always result in a negative value, demonstrating that it concerns an exergy output or in other words an theoretical availability of exergy[10].

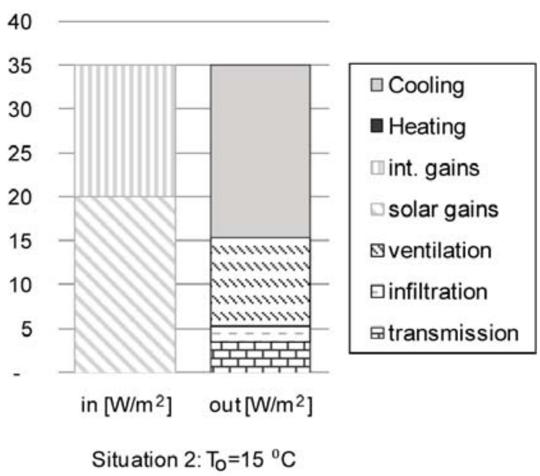


Figure 2.21: Energy balance for a cooling demand situation at $T_0>T_r$.

Equations for detailed exergy demand calculation of cooling demand at $T_0<T_r$

$$Q_{dd,c} = Q_{dem,tot} \quad (2.62)$$

$$Ex_{dd,c} = Q_{dd,c}\left(1 - \frac{T_0}{T_r}\right) \quad (2.63)$$

The results of these equations can be found in the next paragraph.

2.2.2.9 Comparison of the simplified and detailed exergy demand calculation methods

For the steady state comparison a simple commonly existing office space has been used. Its main characteristics are shown in Table 2.3 below.

Table 2.3: Characteristics of the office building taken as example here.

Office space, corner 5,4 x 5,4 x 3 m	
Floor space:	29 m^2
Closed exterior façade surface	19,44 m^2
Glass surface	13 m^2
Internal gains	25 W/m^2
Infiltration rate	0,6 1/h

Two test cases have been used to compare the results from the detailed and simplified exergy demand calculations methods:

A comparison of 4 situations with constant T_0, but changing air change rate and insulation values for the building, keeping the energy demand the same for all cases;

A comparison of 5 situations with constant room characteristics and changing outdoor conditions (temperature and solar radiation).

Steady state comparison 1

In Table 2.4 and Figure 2.22 the results of the exergy demand according to the simplified and detailed calculation methods are shown. For all cases the following values are used:

outdoor air temperature T_0 = 5 °C (278 K)
indoor air temperature T_r= 20 °C (298 K)
Solar radiation on façade surface = 120 W/m^2 (winter situation)

The values for air change rate and average U value (average of closed façade and glass surface) is chosen in such a way that the heat demand of all cases is the same.

Discussion of the results:

As it can be expected the exergy demand in all cases is much smaller than the energy demand. The ratio between the two is shown in the quality factor of the demand.

As could also be expected, the detailed exergy demand (which is the sum of the demand related to ventilation air and the demand related to heat) is

Table 2.4: Results from the simplified and detailed exergy demand calculation methods for three building cases with equal energy demand but different characteristics (insulation value and air change rate).

	Case 1a	Case 1b	Case 1c	Case 1d
Average U value [W/m^2K]	3.5	2.6	1.2	0.8
Air change rate [h^{-1}]:	0.5	1.5	2.5	3.5
Energy demand [W/m^2]	14	14	14	14
Exergy demand simple [W/m^2]	0.74	0.74	0.74	0.74
Exergy demand detailed [W/m^2]	0.55	0.24	0.12	0.11
Exergy factor simple	5.1%	5.1%	5.1%	5.1%
Exergy factor detailed	3.8%	1.7%	0.9%	0.7%
Ex_detailed/Ex_simple [-]	0.74	0.33	0.17	0.14

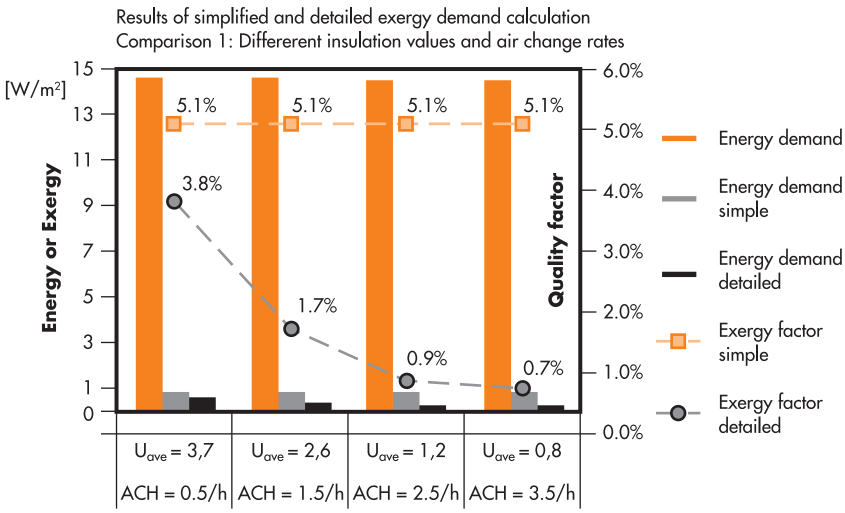


Figure 2.22: Results from the simplified and detailed exergy demand calculation methods for four situations with equal energy demand but different characteristics (insulation value and air change rate).

Table 2.5: Results from the simplified and detailed exergy demand calculation methods for three building cases with equal energy demand but different outdoor temperature and solar radiation.

	Case 2a	Case 2b	Case 2c	Case 2d	Case 2e
T_0 =	-10°C	0°C	5°C	10°C	30°C
Solar radiation [W/m²]:	50	100	120	300	600
Energy demand [W/m²]	70.08	32.83	14.87	-39.71	-110.29
Exergy demand simple [W/m²]	7.18	2.24	0.76	-0.68	1.85
Exergy demand detailed [W/m²]	4.21	0.95	0.20	-0.68	1.77
Exergy factor simple [-]	0.102	0.068	0.051	0.017	-0.017
Exergy factor detailed [-]	0.060	0.029	0.013	0.017	-0.016
Ex,detailed / Ex,simplified [-]	0.587	0.424	0.257	1.000	0.954

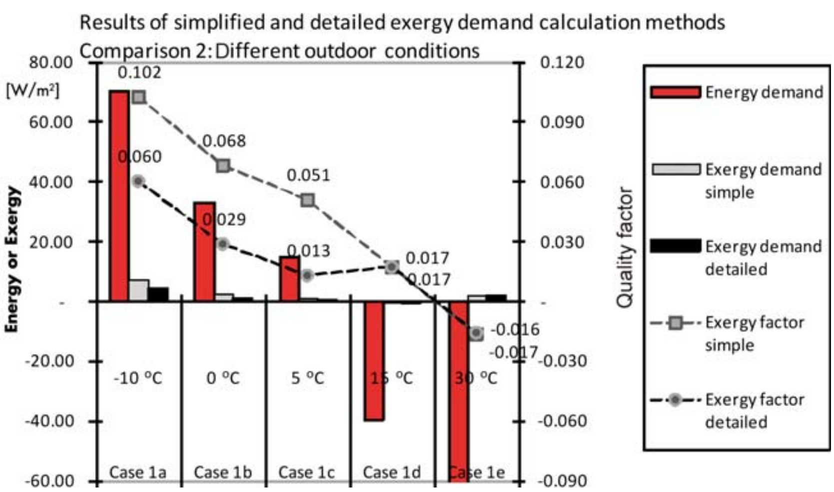


Figure 2.23: Results from the simplified and detailed exergy demand calculation methods for three building cases with equal energy demand but different outdoor temperature & solar radiation.

smaller than the simplified demand calculation.

Since the energy demand and the temperatures are constant the simplified exergy demand is also constant. Due to the different contribution of ventilation and transmission losses however the detailed demand is different for all cases.

It is shown that by decreasing transmission losses and increasing ventilation rates (and losses in this example), the exergy demand becomes smaller, even though the energy demand is the same[11].

From these cases it can be concluded that the ideal demand depends not only on the indoor and outdoor temperatures and the resulting energy demand, but also on the distribution of the losses between ventilation losses and (possibly) remaining net losses. It is noted that the ideal minimum demand is calculated, which is only based on the energy balance of the building 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, which can cause the need for fan energy. This should be taken into account in the analysis of the ventilation system.

Steady state comparison 2

In Table 2.5 and Figure 2.23 the results of the exergy demand according to the simplified and detailed calculation methods are shown. On the left axis the energy and exergy demands (in W/m²) are shown; on the right axis the quality factor (Ex_{dem}/Q_{dem}) of the demand is plotted. A negative energy demand means there is a demand for cooling. A negative exergy demand means there is a demand for exergy output, which means there is not a real exergy demand but theoretically exergy is available. The quality factor has a positive value if the energy and exergy flow are in the same direction.

Discussion of the results:

As in comparison 1 the exergy demand in all cases is much smaller than the energy demand. The closer T_r is to the environment the smaller the exergy factor.

Likewise, the detailed exergy demand (which is the sum of the demand related to ventilation air and the demand related to heat) is smaller than the simplified demand calculation. The closer T_r is to the environment the bigger the difference between the simplified and detailed approach.

A special case is of course the cooling demand at $T_r > T_0$ (Case 1d). In this case this represents a required heat output at T_r, which is why the results are the same for the simplified and the detailed approach (see section 2.2.2.6)

Comparison using dynamic analyses

In a dynamic TRNSYS simulation the simplified and detailed method are also compared.

The graph below shows:

- pink line = the energy demand for heating (the drop in the middle of the day is caused by solar gains)
- blue line = simplified exergy demand,
- green line = detailed exergy demand
- grey line = exergy demand caused only by ventilation.

When there is no ventilation the blue and green line are (obviously) the same.

When zooming in to the building in a detailed way it is recommended to use the detailed calculation method. Especially when trying to optimize heating and ventilation systems at building level the detailed approach should be used.

It is again mentioned that both methods only include thermal exergy. When (de)humidification is required the detailed method should be used and the exergy related to ventilation air should include the chemical exergy related to the composition of the required conditions of the ventilation air (Sakulpipatsin 2008).

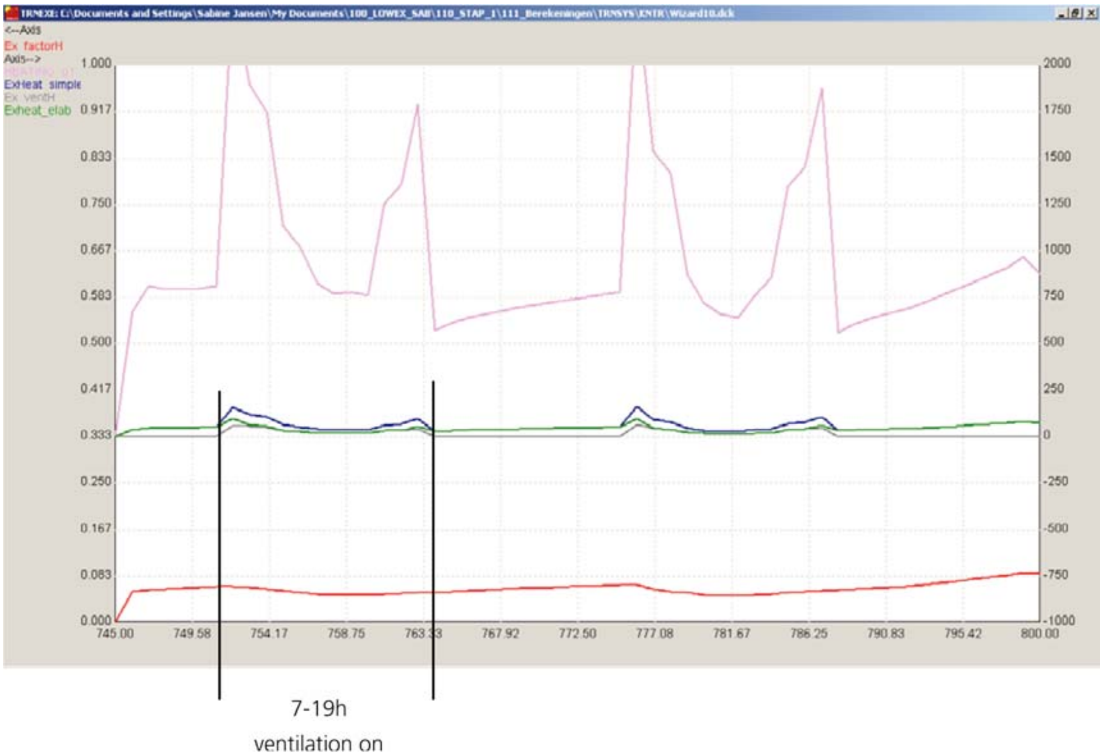


Figure 2.24: Dynamic exergy analysis of three days: comparing simplified and detailed calculation method.

Conclusions

The exergy demand is only up to around 10% of the energy demand (depending on T_0 and T_r), for both the simplified and the detailed calculation method. Comparing only the exergy demands however the difference between the simplified and detailed approach is quite substantial. The exergy demand as calculated using the detailed method is lower than the results of the simplified exergy demand calculation. The difference becomes bigger if T_r approaches T_0 and if large air changes are assumed. The simplified calculation method is easy to use, while the detailed method requires much more equations. Therefore it is recommended to use the simplified method when looking at a total energy supply system of a building (from building to primary energy source) in a preliminary design phase.

Detailed exergy balance of a building zone

Even though the exergy balance cannot be used to determine the exergy demand, it can give insight in the exergy transfers related to the different flows of energy and matter across the system boundaries of the and to the exergy destroyed within the building zone. The basic exergy balance equation as shown in section 2.1.8 can be adapted to the building zones, which are considered to be a control volume with energy and matter crossing the system boundaries.

As is done for energy, all exergy flows are defined as inputs, so that an exergy output will automatically have a negative value. The exergy balance can then be written as follows:

$$Ex_{trans} + Ex_{\text{int}} + Ex_{sol} + Ex_{vent} + Ex_{\text{inf}} + Ex_{dem} - \Delta Ex_{syst} - Ex_{irrev} = 0 \qquad (2.64)$$

Where:

Ex_{trans} =	the exergy input of heat transfer between the walls and the zone (due to transmission and storage)
Ex_{int} =	the exergy input of heat transfer from internal gains
Ex_{sol} =	the exergy input of heat transfer from the sun into the zone
Ex_{vent} =	net exergy input due to ventilation (= exergy of ingoing air – exergy of outgoing air)
Ex_{inf} =	net exergy input due to infiltration (= exergy of ingoing air – exergy of outgoing air)
Ex_{dem} =	the exergy input required to provide the energy demand (for detailed demand this exists of two parts)
Δex_{syst} =	the exergy increase of the system (thermal zone)
Ex_{irrev} =	the exergy destroyed through thermodynamic irreversibilities

According to equation 2.6 and 2.18 the equations to determine the exergy of flows of heat and matter into and out of a control volume can be found:

$$Ex_{trans} = Q_{trans} \cdot \left(1 - \frac{T_0}{T_{trans}}\right) \tag{2.65}$$

$$Ex_{\text{int}} = Q_{\text{int}} \cdot \left(1 - \frac{T_0}{T_{\text{int}}}\right) \tag{2.66}$$

$$Ex_{sol} = Q_{sol} \cdot \left(1 - \frac{T_0}{T_{sol}}\right) \tag{2.67}$$

$$Ex_{vent} = Q_{vent} \cdot \left(1 - \frac{T_0}{(T_r - T_0)} \ln \frac{T_r}{T_0}\right) \tag{2.68}$$

$$\begin{aligned} Ex_{vent} &= Ex_{vent,in} - Ex_{vent,out} \\ &= 0 - \dot{m} \cdot c_p \cdot (T_r - T_0) \cdot \left(1 - \frac{T_0}{(T_r - T_0)} \ln \frac{T_r}{T_0}\right) \end{aligned} \tag{2.69}$$

$$Ex_{\text{inf}} = Q_{\text{inf}} \cdot \left(1 - \frac{T_0}{(T_r - T_0)} \ln \frac{T_r}{T_0}\right) \tag{2.70}$$

For the exergy demand there are two options: the simplified and the detailed calculation method. The equations needed are taken from section 2.2.2.5 and section 2.2.2.6.

For the temperature of the ideal heating or cooling it is chosen to use the operative room temperature T_{op}, which is the average of the indoor air temperature and the weighted mean surface temperature of all inside surfaces.

For the temperature of the solar and internal gains it also the operative room temperature is used, since this is the temperature at which the solar gains are entering the zone (after being absorbed by the walls and other mass in the building). Also, for a cooling case the solar and internal gains represent an exergy output, (since it takes away the coolness), due to the fact that they are increasing the temperature of the zone at T_{op} (i.e. operative temperature)[12]. Assuming the gains to enter the zone at T_{op} is also in accordance with the system boundaries as shown in Figure 2.19.

Exergy balance of heating case

For a heating case the exergy balance of the simplified and the detailed approach (for T_0 = 5 °C) are shown below. It can be seen that the exergy assumed to be destroyed within the zone is greater for the simplified approach than for the detailed approach, as could be expected.

Exergy balance of cooling case at T_r>T_0

The cooling case at T_i>T_0 is a complex case to understand: the room contains warm exergy due to T_i>T_0. However, this warm exergy has to be reduced in order to maintain a comfortable (not too warm) temperature in the zone. Thus both energy and exergy outputs are desired outputs:

- The energy outputs (transmission, ventilation and infiltration) are desired and also represent desired exergy outputs.
- The additional required energy output (cooling demand) represents a desired exergy output of the system at T_{op} as well (the temperature of the system comes closer to the environment). The simplified and detailed approaches come to the same result since the cooling output is heat transfer at T_{op}. (In reality it would be preferred to increase ventilation, but assuming the ventilation to be a fixed value, additional cooling is heat transfer at T_{op})
- The destroyed exergy (due to mixing of heat at T_r and air) is also a desired destruction.

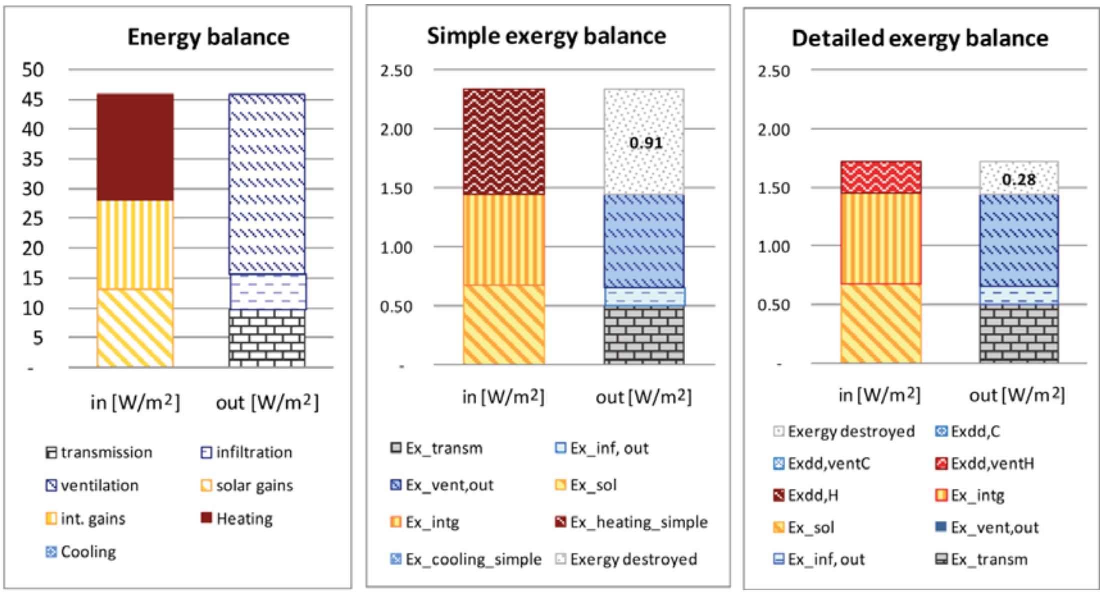


Figure 2.25: Energy and exergy balance for heating case.

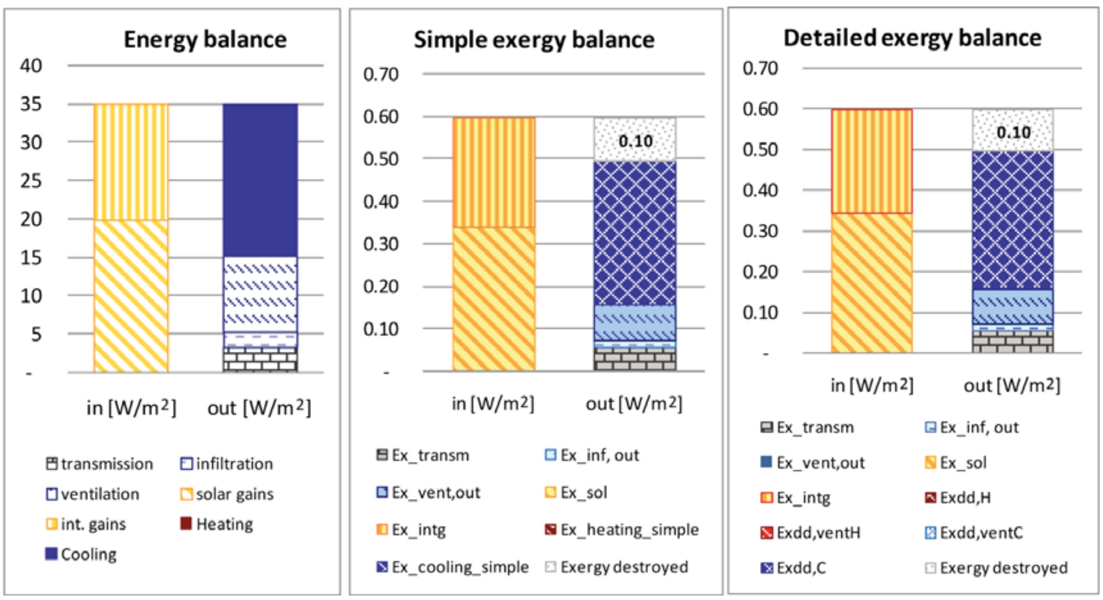


Figure 2.26: Energy and exergy balance for cooling case at T>T_0.

Exergy balance of cooling case at $T<T_0$

When $T<T_0$ all energy flows except active cooling represent unwanted gains, reducing the cool exergy of the room. The cooling is an energy output, but represents an (the only) exergy input. The difference between the simplified and the detailed demand calculation is that in the last one part of the cooling is achieved by precooling the ventilation air. This results in less mixing of different temperatures in the zone and thus to less exergy destruction.

Calculating solar and internal gains at T_{sun} and T_{gain}

When calculating the exergy from solar and internal gains using the temperature of the sun (6000 K) and the gains (for example 50°C), this means your system boundaries are taken up to where this temperature actually exists. This also means you assign all exergy destruction that takes place to the zone. Assuming solar and internal gains to enter at T_{sun} (6000K) and T_{gain} (e.g. 50°C) results in the following exergy balances for the same situation as the above (T_0 = 5 °C).

As can be seen large exergy destruction takes place within the zone, which is almost equal to the exergy supplied by the sun. This depiction is considered to give less insight than the above depiction. Therefore it is recommended to use the operative temperature for the solar and internal gains as well, and to account for the destruction of the potential of the sun and the internal gains outside the building boundaries. This can be done regarding the sun as a passive source with high potential which is not being used.

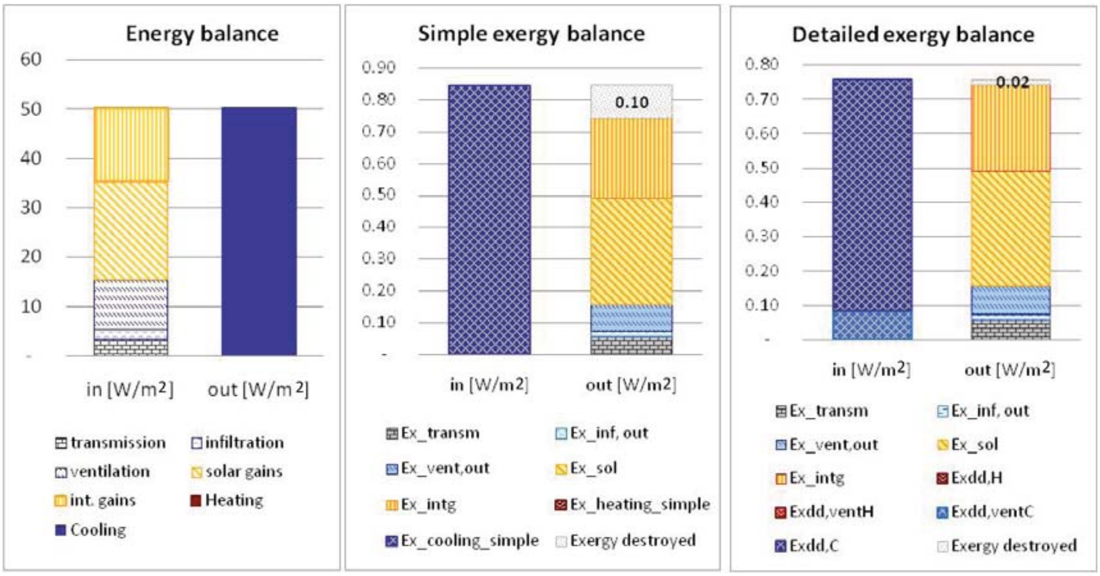


Figure 2.27: Energy and exergy balance for cooling case at $T<T_0$.

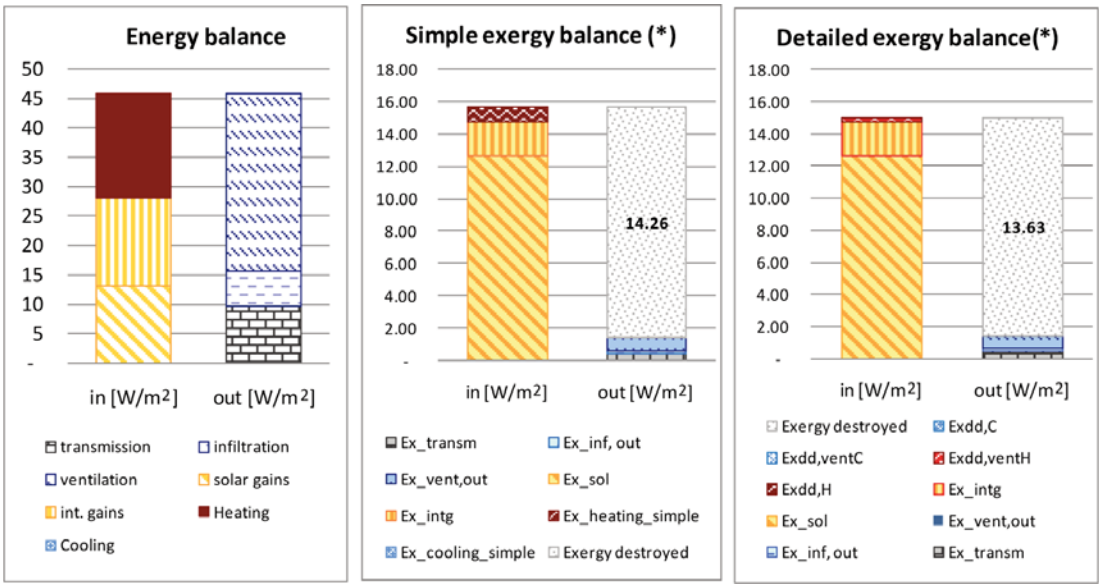


*Figure 2.28: Energy and exergy balance for heating case; *assuming solar and internal gains to enter at T_{sun} =6000 K and T_{gain} =50°C.*

2.2.2.10 Conclusions & Guidelines

As it has been explained the exergy demand of a building is defined as the minimum amount of work required to provide the required energy (heating) or remove the required energy (cooling). For the minimum amount of work the energy should be provided at the lowest quality possible. The calculation of the exergy demand is therefore based on providing the energy at the lowest quality possible.

It has been shown that the exergy demand cannot be calculated from the exergy balance, since an exergy balance includes two unknown components: the exergy demand and the part of destroyed exergy. Therefore the calculation of the exergy demand is based on the energy balance, keeping in mind the arguments mentioned above.

This chapter has discussed the essential difference between two situations where there is a cooling demand:

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 represents a required exergy input, thus an exergy demand, since the system (building) is brought to a temperature further from the environmental temperature. In the second case the cooling demand actually represents an exergy output, meaning there is theoretically exergy available, since the system is brought to a temperature closer to the environmental temperature.

Two different ways of calculating the exergy demand are explained. The simplified method as it has been introduced by Schmidt (2004), is based on the assumption that all energy is supplied or removed at the indoor air temperature. The detailed exergy demand calculation differentiates between the exergy demand related to matter (air) and the exergy demand related to heat. To calculate the part of the demand used to heat ventilation air and the part used to compensate for other losses, the building zone is regarded as a control volume with an input of air and an input of heat (or cold, which is an output).

Comparing the two methods it has been shown that for both cases the exergy demand is only up to around 10% of the energy demand (depending on T_0 and T_r). Comparing only the exergy demands however the difference between the simplified and detailed approach is quite substantial. The difference becomes bigger if T approaches T_0 and if large air changes are assumed. The simplified calculation method is easy to use, while the detailed method requires much more equations.

Therefore it is recommended to use the simplified method when looking at a total energy supply system of a building (from building to primary energy source) in a preliminary design phase. When zooming in to the building in a detailed way it is recommended to use the detailed calculation method. Specially when trying to optimize heating and ventilation systems at building level the detailed approach should be used. It is noted that both methods only regard the thermal part of the exergy.

2.3 Mathematical models

2.3.1 Exergy and thermal comfort

Low exergy systems for heating and cooling of buildings, similarly as buildings themselves, should not solely be designed to be energy or exergy efficient but, above all, they need to provide adequate comfort conditions in the built environment. Physics with respect to the built environment and its technology must be in harmony with human physiology and psychology. Thus, it is vitally important to have a clear understanding of the exergy balance of the human body in order to understand in which way thermal energy demands in buildings could be provided with minimum losses while guaranteeing comfort conditions. This section gives a clear and detailed introduction on the exergy processes in the human body. Based on these mathematical models for human body exergy balance, it has been determined that minimum exergy consumption within human body occurs at thermally neutral conditions and can be achieved at higher mean radiant temperatures and lower air temperatures during the heating period (Ala-Juusela, 2003). The experience of many building engineers and scientists indicate that these conditions of minimum exergy consumption in human body are coherent with maximum level of thermal comfort. These conditions might be achieved with low-temperature heating and high temperature cooling systems (i.e. radiant systems) which supply the required energy demands at a temperature very close to the indoor temperature, being thereby low-exergy heating and cooling systems. Figure 2.29 shows the human-body exergy consumption rates for winter and summer conditions are given: the former is shown as a function of mean radiant temperature and air temperature and the latter as a function of mean radiant temperature and air movement. It was found from a series of analyses having done so far that there are the minimum values of human-body exergy consumption rate both in winter and in summer. These findings suggest that the development of so-called low-exergy systems for heating and cooling are on the right track.

2.3.1.1 Human body exergy consumption

Animals including human being live by feeding on organic matters containing a lot of exergy in chemical forms. They move muscles by consuming it not only to get their food but also not to be caught as food by other animals. All of such activity realized by their body structure and function is made possible by chemical-exergy consumption.

The chemical-exergy consumption brings about quite a large amount of "warm" exergy. In fact, this is the exergy consumed effectively by those animals called homeotherms including human being to keep their body-core temperature almost constant, at which various bio-chemical reactions necessary for life proceed smoothly at a controlled rate. This temperature level, as we know by our own experience

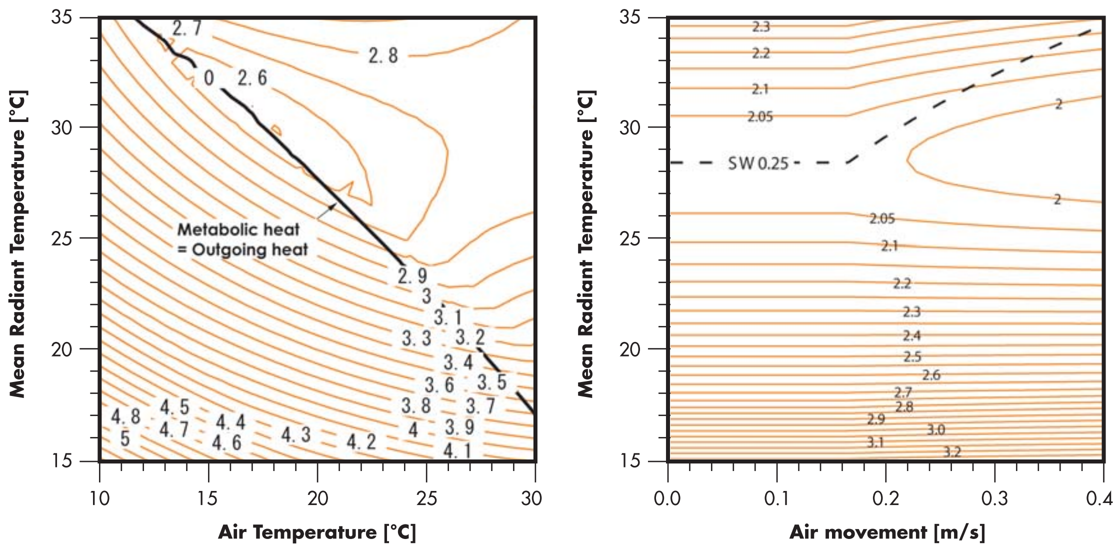


Figure 2.29: (left): Relationship between human body exergy consumption rate, represented by the unit W/m² (body surface), and the human body's environmental temperature under a winter condition (0°C; 40% relative humidity). There is a set of room air temperature (18 to 20°C) and mean radiant temperature (23 to 25°C) which provides the body with the lowest exergy consumption rate;
(right): Relationship between human body exergy consumption rate, of which the unit is W/m² (body surface), and the combination of mean radiant temperature and air movement under a summer condition (33°C; 60% relative humidity).

through usually unconsciousness, is generally higher than the environmental temperature.

There are two kinds of animals from the viewpoint of thermoregulation of their body temperature: homeotherms (endotherms) as described just above and poikilotherms (ectotherms). To the former belong those animals maintaining their body temperature at an approximately constant level regardless of their environmental temperature variations and to the latter those animals whose body temperature fluctuates in accordance with their environmental temperature variations.

Either homeotherms or poikilotherms generate a certain amount of entropy in proportion to the exergy consumption inside their bodies in due course of life and they must excrete the generated entropy into their environmental space by long-wavelength (LW) radiation, convection, conduction, and evaporation. It is vitally important for the homeotherms to be able to get rid of the generated entropy immediately and smoothly to be alive because of their relatively large rate of exergy consumption. We humans are no exception.

In what follows, we discuss the exergy balance of human body as a system of homeotherms and then its relation to thermal comfort in the built environment.

2.3.1.2 Water balance

We drink water several times a day and also excrete water with waste, namely urinate, several times a day. The urination is the primary way of discharging the water from our body, but there are two other ways: one is by breathing and the other by secreting sweat. The former is originated from the secretion and evaporation of water inside the internal space of the lung and the latter takes place at our skin surface.

The primary purpose for us to drink water is to maintain the concentration of various cations, anions and organic compounds necessary for all of roughly 60 trillion living cells within our body, while at the same time to dispose of the used blocks of amino-acids and others by dispersing them into the water and excrete as urination, and the second purpose, equally important as the primary one, is to maintain the body-core temperature at an almost constant level regardless of the fluctuations of surrounding temperature.

In order for keeping the dynamic equilibrium (Guggenheim, 1991) of human body, the disposal of generated entropy due to chemical-exergy consumption is of vital importance. The thermal-exergy consumption within the human body is, in other words, for such inevitable entropy disposal.

Table 2.6 summarizes the approximate amounts of water taken in and given off by an average person for one day (Fujimoto, 1983). The water supplied to the body by drinking and by eating food amounts to 86% and the rest is generated by biochemical reactions inside the body. The chemical compounds contained by most of the foodstuffs are composed of carbon and hydrogen atoms in addition to nitrogen in proteins so that their decomposition under the condition at body temperature with a help of various enzymes and with the existence of much oxygen molecules brought by breathing results in the production of carbon-dioxide and water molecules as by-products of the primary production of building blocks and a variety of proteins made of amino-acids as building blocks for our body cells and ATP, adenosine tri-phosphate, as fuel.

In short, the hydrogen atoms contained by various organic matters such as glucose, proteins, and fatty acids react with the oxygen atoms supplied by breathing and thereby the water molecules are generated. This implies that the "wet" exergy of water is produced by the consumption of chemical exergy originally contained by food.
The output of water amounts to 2500 ml/day, which is the same as the input. The 60% of water output is due to urination and a half of the rest, 20%, is due to breathing and the other half is due to sweat secretion by 80%, namely 16% of the total output, and the excretion with waste matter by 20%, namely 4% of the total.

Both drinking and urinating are the intermittent behaviours so that our body weight changes from time to time, but if we take a look at our average body weight at one-day intervals, there is no change due to water inflow and outflow. Therefore we can set up a water-balance equation for the human body at a steady-state condition. The water input equals the water output. An interesting estimation

Table 2.6: Water balance of a human body for one day.

	Input			Output	
	2500 ml	(100)*		2500 ml	(100)
Drinking	1000	(40)	Urination	1500	(60)
Eating food	1150	(46)	Breathing	500	(20)
Metabolism	350	(14)	Sweat secretion	400	(16)
			Excretion with waste matter	100	(4)

* The figures in the brackets are relative amounts to the input or the output in percentage

with respect to the water balance of human body is such that all of water contained by the body is replaced within twenty days or so assuming that the 70% of the body weight of a 70 kg person is comprised of water.

As described in the beginning of this section, human being is one kind of homeotherms, but the temperature of the peripheral part of the body such as hands and foots in particular varies with the surrounding temperature variations. Therefore, let us assume that the human body consists of two subsystems for thermodynamic modelling: the core and the shell as shown in Figure 2.30. The core is one subsystem whose temperature is maintained nearly constant at 37°C almost independently from the variations of surrounding temperature and humidity variations; while on the other hand, the shell is the subsystem whose temperature is rather dependent much on their variations. Between these two systems, there is a circulation of blood, whose rate is variable dependent on external and internal conditions of the body. The steady-state mass balances of these two subsystems with respect to humid air and liquid water can be described in the form of input being equal to output as follows. At the "core" subsystem,

[The inhaled humid air] +
[The liquid water generated by metabolism in the core] +
[The blood flowing into the core from the shell]
= [The exhaled humid air] +
[The blood flowing out of the core to the shell]. (2.71)

At the "shell" subsystem,

[The liquid water generated by metabolism in the shell] +
[The blood flowing into the shell from the core]
= [The liquid water secreted as sweat at the skin surface] +
[The blood flowing out of the shell to the core]. (2.72)

In these equations, all terms of the left-hand side of the equal sign are input and those of the right-hand side are output. The generated liquid water, which appears in each of the above two equations, includes an amount of water absorbed in the course of drinking water and eating food in addition to that generated in the course of metabolism. Combining the two equations yields the water balance equation for the whole human body.

[The inhaled humid air]
+ [The liquid water generated by metabolism in the core]
+ [The liquid water generated by metabolism in the shell]
= [The exhaled humid air]
+ [The liquid water secreted as sweat at the skin surface].
(2.73)

The exhaled humid air is more humid than the inhaled humid air, since it contains the water vapour originating from the liquid water generated in the core. The liquid water to be secreted as sweat at the skin surface is assumed to originate from the liquid water generated in the shell that is expressed at the left hand side of equation 2.73.

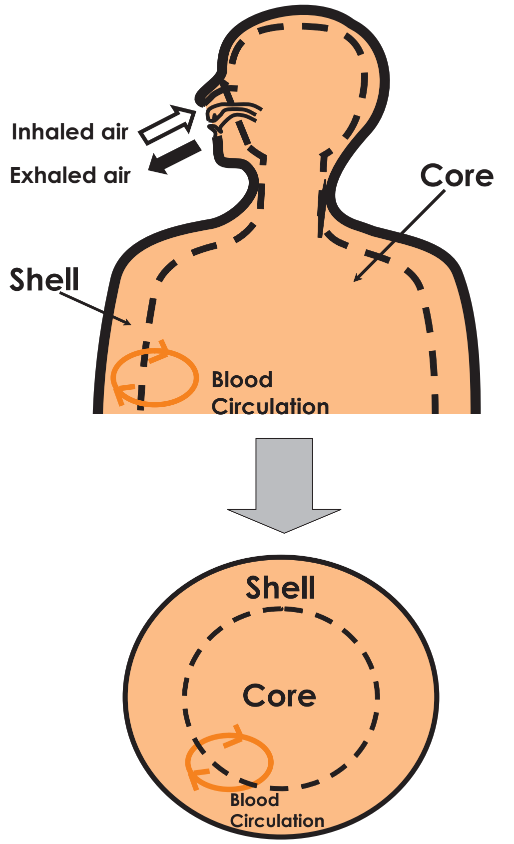


Figure 2.30: Modeling of a human body consisting of two subsystems: the core and the shell. The core is the central portion of the body whose temperature is kept almost constant at 37°C independent of the variations of surrounding temperature and humidity. The shell is the peripheral portion, whose temperature is dependent on the variations of surrounding temperature and humidity and on the level of metabolism.

2.3.1.3 Energy and entropy balances

According to our daily experience, chemical exergy contained within the foodstuffs may seem to be consumed mostly for the production of work, but we must not forget that it is also consumed for maintaining a variety of body structures and functions. From the thermodynamic viewpoint, the human body is a typical dissipative structure, which self-organizes its form by running the "exergy-entropy" process, the chain of exergy supply, its consumption and the resultant entropy generation, and the entropy disposal. The production of work is never realized without chemical exergy consumption for the body structure and its associated function.

If the liquid water contained by foodstuffs is squeezed, then they would burn very well. Although it is only with an imagination, the same would be true for the human body. As described in 2.3.1.2, there is always the water inflow and outflow through the human body. The 65 to 70 % of our body weight is always filled with liquid water so that a sudden rise of body temperature is not likely to happen; if it happened, it could cause an irreversible fatal damage of a complex body structure and function. We can say that the structure and the function of our body are formed by a moderate rate of burning foodstuffs in a special manner with the abundance of water. In due course, a large amount of thermal energy and entropy is produced necessarily.

The thermal energy has to be dumped into the environmental space, because it is accompanied with a lot of entropy generated within the human body for the complex bio-chemical reactions. Otherwise the human body could malfunction as described above.
Let us assume that a human-body system as shown in Figure 2.31 resides in a room space. The temperatures of the human-body, room air, and outdoor air are assumed to be higher in this order. Thermal energy outgoing across the body surface first enters the room space and then flows out into the outdoor environmental space. The liquid water secreted from the sweat glands forms a thin water film over the skin surface and then it evaporates into the room space unless the moisture contained by the room air is saturated. A portion of the room air having the water vapour originating from the human body has to be ventilated so that the room air can always allow the moisture discharged from the human body to disperse.

Most portions of the outside surface of the body-shell are covered by cloth, but the rest is naked; the head, the face, and the hands are exposed usually to the environmental space. The whole shape of human body is complex because of the head, the arms, and the legs hanging on the body centre. Theoretically speaking, it should be possible to set up energy, entropy, and exergy balance equations taking such complexity and non-uniformity into consideration, but the more complicated the equations are, the more unknown variables we have to assume for actual calculation. This could result in little improvement of the accuracy, especially when looking into the exergy balance, and could even bring about such results that are hard to understand. Therefore, we had better make a moderate model with reasonably accurate exergy calculation by compromising two rather opposite requirements, the precision and the simplicity.

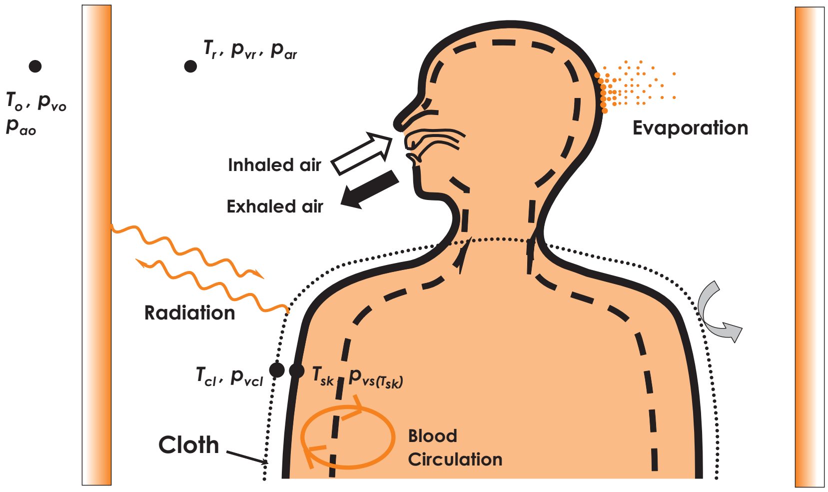


Figure 2.31: Human body must always release the thermal energy generated by bio-chemical reactions into the environmental space by radiation, convection, evaporation and conduction. This is for getting rid of the generated entropy.

Here we start with a two-node energy-balance model of the human body, since it has been used quite extensively by building-science researchers and engineers in the field of heating and cooling in buildings (Gagge et al., 1971; Gagge et al., 1986; Gagge et al., 1972; ASHRAE, 2005). This model was given as the energy balance equation, in which the metabolic energy emission rate as input equals the sum of thermal energy stored within the body and the net thermal energy transfer into the surrounding space by respiration, evaporation, convection and radiation. There is also conduction in reality, but it is neglected and implicitly considered in a portion of convection.

This model has a form convenient for the calculation of body-core, body-shell, and clothing temperatures, but not for that of warm/cool exergy and wet/dry exergy. Therefore, it is necessary to make a little bit of modification of the model.

One modification is to change the net thermal energy transfer due to the humid-air transport by breathing and the evaporation of sweat into five explicit forms of the enthalpy values: those of inhaled and exhaled humid air, those of liquid water produced by metabolism in the body-core and in the body shell, and that of water vapour discharged from the skin surface by evaporation. One other modification is to make the net radiant energy transfer between the human body and his/her surrounding into the explicit forms of radiant energy: one absorbed by the whole of skin and clothing surfaces and the other emitted from the whole of skin and clothing surface.

The modified energy-balance model, the form of which is consistent with the water balance equation 2.73, is expressed as follows.

[Thermal energy emerged by metabolism] (2.74)
+ [Enthalpy of the inhaled humid air]
+ [Enthalpy of the liquid water generated in the core by metabolism]
+ [Enthalpy of the liquid water generated in the shell by metabolism]
+ [Radiant energy absorbed by the whole of skin and clothing surface]
= [Thermal energy stored in the core and the shell]
+ [Enthalpy of the exhaled humid air]
+ [Enthalpy of the water vapor originated from the sweat secreted]
+ [Radiant energy emitted by the whole of skin and clothing surfaces]
+ [Thermal energy transferred by convection from the whole of skin and clothing surfaces into the surrounding air].

Metabolic thermal-energy generation as input on the left-hand side and thermal energy stored within the human-body on the right-hand side are the characteristic difference in the energy balance equation from the water balance equation 2.73. This energy balance equation is set up with an assumption of unsteady-state condition, while on the other hand, the water balance equation with steady-state condition. This energy balance equation assumes that the thermal conduction from the foot to the floor or from the back to the chair is implicitly included in the portion of convective energy transfer. It is also assumed that the output of work is neglected; in other words, this energy balance equation can be applied to the human body at the posture of standing or seating with up to light office work.

All of five terms of the enthalpy values in equation 2.74 must be expressed as the enthalpy differences from the humid air outdoors. This is in order for the actual numerical calculation of exergy balance. This mathematical operation is done by adding the same enthalpy values of outdoor humid air, whose amounts are consistent with water balance equation, if converted into their corresponding mass values, to both sides of the energy balance equation.

It is also necessary to make the two terms of radiant energy be those of radiant energy difference measured from the radiant energy emitted by an imaginary surface at the outdoor air temperature; this is done by adding the same radiant-energy values, which could be emitted from the imaginary surface at outdoor air temperature, to both sides of the energy balance equation.

Such operations applied to the terms of enthalpy and radiant energy are not necessary for other three terms: thermal energy emerged by metabolism, thermal energy stored in the body-core and the bodyshell, and thermal energy transfer by convection.

The sum of the enthalpies of inhaled humid air and the liquid water generated by metabolism in the body-core, which appear on the second and third terms on the left-hand side of equation 2.74 relates to the enthalpy of the exhaled humid air on the right-hand side of the equation. Their difference is the thermal energy discharged by respiration.

The enthalpy value of the liquid water generated in the body-shell by metabolism, which appears on the fourth term of the left-hand side of the energy balance equation relates to the enthalpy of the water vapour originated from the sweat secreted and dispersing into the surrounding space, which appears on the third term of the right-hand side of the energy-balance equation. Their difference is the thermal energy dissipated by evaporation at the skin temperature. The entropy balance equation, which is consistent with equation 2.74 can be written as follows (Isawa et al., 2002; Isawa et al., 2003; Saito and Shukuya, 2001; Saito et al., 2000):

[Thermal entropy given to the body by metabolism] (2.75)
+ [Entropy of the inhaled humid air]
+ [Entropy of the liquid water generated in the core by metabolism]
+ [Entropy of the liquid water generated in the shell by metabolism]
+ [Radiant entropy absorbed by the whole of skin and clothing surfaces]
+ [Entropy generation]
= [Thermal entropy stored in the core and the shell]
+ [Entropy of the exhaled humid air]
+ [Entropy of the water vapor originated from the sweat secreted and dispersing into the surrounding space]
+ [Radiant entropy discharged from the whole of skin and clothing surfaces]
+ [Thermal entropy given off by convection from the whole of skin and clothing surfaces].

The first term in the left-hand side of this equation, the entropy given to the body by metabolism, is the entropy generated by all of bio-chemical reactions in order to keep the body structure and function. The term of "entropy generation" appeared in the end of the left-hand side of the above equation, which is unique in entropy balance equation being distinct from the energy balance equation, is due not only to thermal energy dispersion caused by temperature difference between the body-core and the body-shell, but also due to the dispersion of water molecules into the surrounding moist air. The pressure difference in water vapour between the wet skin surface and the surrounding space of the body plays a key role in the latter case. Mathematical operations similar to the energy balance equation are also necessary for the entropy balance equation to be applied to develop the exergy balance equation. There are three such operations in the case of entropy balance equation.

The first two of them are exactly the same as those applied to the energy balance equation. One of them is to make the five terms of entropy associated with the inhaled and exhaled humid air, the liquid water generated by metabolism in the body-core and in the body-shell, and the water vapour discharged from the skin by evaporation, into the respective five terms of entropy differences measured from the enthalpy value of the humid air outdoors. The other is to make the two terms of radiant entropy be those of radiant entropy measured from the radiant entropy emitted from an imaginary surface at the outdoor air temperature.

The third of the mathematical operations required is unique in entropy balance equation. Let us look at the third term of the right-hand side of the entropy balance equation 2.75. The dispersion of water vapour takes place in the surrounding space, where there is room air. In other words, the water vapour does not disperse into a space of vacuum. Therefore, we need to assume a corresponding amount of dry air, which is to disperse mutually with water vapour to become a portion of room air with a certain value of humidity. Its entropy value is added to both sides of equation 2.75 to be applied for developing the exergy equation. The idea of this operation is again exactly the same as that to be done for entropy values relating to mass transport by respiration and sweat secretion and also for radiant entropy values.

2.3.1.4 Thermal exergy balance

Thermal exergy balance of human body can be derived by combining the energy balance equation and the entropy balance equation, both of which are the resultant equations of the mathematical operations described above, together with the environmental temperature for exergy calculation, which is outdoor air temperature.

One may wonder if the environmental temperature is room air temperature or operative temperature, but it is neither of them, except a case that the human body is assumed to be outdoors, for which the surrounding air temperature of the human body turns again to be exactly the outdoor air (or operative) temperature. If an overall investigation of the human-body exergy balance is made together with space-heating or –cooling system's exergy balance, the environmental temperature to be taken must be the same for both human body and space heating or cooling system (see 2.1.2).

[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].
(2.76)

The first term of equation 2.76 is the warm exergy produced as the result of chemical exergy consumption for a variety of cellar activities, mainly for the contraction of muscle tissues, the composition of proteins, and the sustenance of the relative concentrations of various minerals in the body cells. The metabolic exergy balance can be expressed as follows:

[Chemical exergy supply]
– [Exergy consumption]
= [Exergy supply for body function]
+ [Warm exergy generated]
(3.7)

The chemical exergy supplied to the human body by eating food is the exergy trapped by the special compositions of carbon, hydrogen, oxygen, nitrogen and other miscellaneous atoms, which originates from the short-wavelength radiant exergy provided by solar radiation. The hydrogen atoms in the liquid water generated by metabolism originate from the hydrogen atoms contained within the liquid water molecules absorbed by the roots of plants for photosynthesis. All of the warm and wet exergies generated within the human body come from the matters brought by other living creatures. This is the important fact that we should keep in mind. The second term of the right-hand side of equation 2.77 is exactly the warm exergy appeared in the first term of equation 2.76.

The exergy-consumption appeared in the last term of the left-hand side of equation 2.76 is due to two kinds of dispersion: one is thermal dispersion caused by the temperature difference between the body core, whose temperature is almost constant at 37°C, and the body shell, namely the skin, whose temperature range from 30 to 35°C, and the clothing surface, whose temperature range from 20 to 35°C; the other is dispersion of liquid water into water vapour, in other words, free expansion of water molecules into their surrounding space.

The chemical exergy consumption appeared in equation 2.68 usually amounts to more than 95% of chemical exergy supply. It implies that the amount of entropy generated in due course is very large, since the amount of entropy generation is exactly proportional to that of exergy consumption. All terms in the right-hand side of equation 2.76 except the first term, exergy storage, play important roles respectively in disposing of the generated entropy due to chemical exergy consumption within the human body, while at the same time disposing of the generated entropy due to thermal exergy consumption appeared in equation 2.76. These processes of outgoing exergy flow together with exergy consumption influence very much on human well-being: health and comfort.

Tables 2.7 a), b) and c) summarize the details of all terms of equation 2.76 to make numerical calculation and are used for the tool development described in 3.6.

The procedure of calculation is as follows:

1) Assume six variables: metabolic energy generation rate; amount of clothing in clo unit; surrounding air temperature; surrounding air relative humidity; mean radiant temperature; air current.
2) Calculate the body-core temperature, the bodyshell (skin) temperature, the clothing-surface temperature, and the skin-wettedness. These values can be determined by following the procedure given by Gagge et al.(1971; 1972; 1986).
3) Calculate the sweat-secretion rate using the skin wettedness.
4) Substitute the results of three calculated temperatures and the sweat-secretion rate into the terms given in Table 2.7-a) and calculate their values except the term of exergy consumption.
5) Substitute the values of exergy obtained from the above calculation into eq. 2.76 and then calculate the value of exergy consumption.

The infinitesimal time interval dt given in Table 2.7-a) is replaced to be the finite increment of time, Δt, e.g. 360 seconds, for actual numerical calculation. The same applies to the values of dT_{cr} and dT_{sk}. For example, The infinitesimal temperature change dTcr is replaced to be a finite difference in temperature between time n and time n-1, so that the skin temperature at time n is calculated from that at time n-1.

If the average rate of exergy input, consumption, storage and output are to be calculated, then the values obtained from the calculation above are divided by the assumed finite increment of time.

Table 2.7: The mathematical formulae of the respective terms in eq.2.76.

Warm exergy generated by metabolism	$M(1-\frac{T_o}{T_{cr}})dt$
Warm/cool and wet/dry exergies of the inhaled humid air	$V_{in}\left[\left\{c_{pa}(\frac{\mathfrak{M}_a}{RT_{ra}})(P-p_{vr})+c_{pv}(\frac{\mathfrak{M}_w}{RT_{ra}})p_{vr}\right\}\left\{(T_{ra}-T_o)-T_o\ln\frac{T_{ra}}{T_o}\right\}+\frac{T_o}{T_{ra}}\left\{(P-p_{vr})\ln\frac{P-p_{vr}}{P-p_{vo}}+p_{vr}\ln\frac{p_{vr}}{p_{vo}}\right\}\right]dt$
Warm and wet exergies of the liquid water generated in the core by metabolism	$V_{w-core}\rho_w\left[c_{pw}\left\{(T_{cr}-T_o)-T_o\ln\frac{T_{cr}}{T_o}\right\}+\frac{R}{\mathfrak{M}_w}T_o\ln\frac{p_{vs}(T_o)}{p_{vo}}\right]dt$
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	$V_{w-shell}\rho_w\left[c_{pw}\left\{(T_{sk}-T_o)-T_o\ln\frac{T_{sk}}{T_o}\right\}+\frac{R}{\mathfrak{M}_w}T_o\left\{\ln\frac{p_{vs}(T_o)}{p_{vo}}+\frac{P-p_{vr}}{p_{vr}}\ln\frac{P-p_{vr}}{P-p_{vo}}\right\}\right]dt$
Warm/cool radiant exergy absorbed by the whole of skin and clothing surfaces	$f_{eff}f_{cl}\sum_{j=1}^{N}a_{pj}\varepsilon_{cl}h_{rb}\frac{(T_j-T_o)^2}{(T_j+T_o)}dt$
Exergy consumption rate, which is only for thermoregulation	$\delta S_g T_o$
Warm exergy stored in the core and the shell	$Q_{core}(1-\frac{T_o}{T_{cr}})dT_{cr}+Q_{shell}(1-\frac{T_o}{T_{sk}})dT_{sk}$
Warm and wet exergies of the exhaled humid air	$V_{out}\left[\left\{c_{pa}(\frac{\mathfrak{M}_a}{RT_{cr}})(P-p_{vs}(T_{cr}))+c_{pv}(\frac{\mathfrak{M}_w}{RT_{cr}})p_{vs}(T_{cr})\right\}\left\{(T_{cr}-T_o)-T_o\ln\frac{T_{cr}}{T_o}\right\}+\frac{T_o}{T_{cr}}\left\{(P-p_{vs}(T_{cr}))\ln\frac{P-p_{vs}(T_{cr})}{P-p_{vo}}+p_{vs}(T_{cr})\ln\frac{p_{vs}(T_{cr})}{p_{vo}}\right\}\right]dt$
Warm/cool exergy of the water vapor originating from the sweat and wet/dry exergy of the humid air containing the evaporated sweat	$V_{w-shell}\rho_w\left[c_{pv}\left\{(T_{cl}-T_o)-T_o\ln\frac{T_{cl}}{T_o}\right\}+\frac{R}{\mathfrak{M}_w}T_o\left\{\ln\frac{p_{vr}}{p_{vo}}+\frac{P-p_{vr}}{p_{vr}}\ln\frac{P-p_{vr}}{P-p_{vo}}\right\}\right]dt$
Warm/cool radiant exergy discharged from the whole of skin and clothing surfaces	$f_{eff}f_{cl}\varepsilon_{cl}h_{rb}\frac{(T_{cl}-T_o)^2}{(T_{cl}+T_o)}dt$
Warm/cool exergy transferred by convection from the whole of skin and clothing surfaces into the surrounding air	$f_{cl}h_{ccl}(T_{cl}-T_{ra})(1-\frac{T_o}{T_{cl}})dt$

Table 2.7 (a): The mathematical symbols used in Table 2.7.

Every term in Table 3.2-a) is expressed for the infinitesimal period of time, and for one squared-meter of human-body surface. The symbols used in the formulae from the top to the bottom denote as follows.

M	metabolic energy generation rate [W/m^2]
T_o	outdoor air temperature as environmental temperature for exergy calculation [K]
T_{cr}	body-core temperature [K]
t	time [s] and dt is its infinitesimal increment
V_{in}	volumetric rate of inhaled air [(m^3/s)/ m^2]
c_{pa}	specific heat capacity of dry air [J/(kg K)] (=1005)
$\mathfrak{M}_a$	molar mass of dry air [g/mol] (=28.97)
R	gas constant [J/(mol K)] (=8.314)
T_{ra}	room air temperature [K]
P	atmospheric air pressure [Pa] (=101325)
p_{vr}	water-vapor pressure in the room space [Pa]
c_{pv}	specific heat capacity of water vapor [J/kg K] (=1846)
$\mathfrak{M}_w$	molar mass of water molecules [g/mol] (=18.05)
p_{vo}	water-vapor pressure of the outdoor air [Pa]
V_{w-core}	volumetric rate of liquid water generated in the body core, which turns into water vapor and is exhaled through the nose and the mouth [(m^3/s)/ m^2]
ρ_w	density of liquid water [kg/m^3] (=1000)
c_{pw}	specific heat capacity of liquid water [J/(kg K)] (=4186)
$p_{vs}(T_o)$	saturated water-vapor pressure at outdoor air temperature [Pa]
$V_{w-shell}$	the volumetric rate of liquid water generated in the body shell as sweat [(m^3/s)/ m^2]
T_{sk}	skin temperature [K]
f_{eff}	the ratio of the effective area of human body for radiant-heat exchange to the surface area of the human body with clothing (=0.696~0.725)
f_{cl}	the ratio of human body area with clothing to the naked human body area (=1.05~1.5)
a_{pj}	absorption coefficient between the human body surface and a surrounding surface denoted by j [dimensionless] (it can be assumed to be equal to configuration factor, the ratio of incoming diffuse radiation to the human body to the diffuse radiation emitted from surface j in most cases);
ε_{cl}	emittance of clothing surface [dimensionless](its value is usually higher than 0.9)
h_{rb}	radiative heat-transfer coefficient of a black surface [W/(m^{2}K)] (=5.7~6.3)
T_j	temperature of surface j [K]
δS_g	amount of entropy generation during the infinitesimal period of time [(Onnes/s)/m^2] ("Onnes" is the unit of entropy, exactly equal to J/K. "Onnes" comes from H. Kammerlingh-Onnes, a Dutch scientist , who first succeeded in liquefaction of helium and reaching 4.1 K in due course[14].)
Q_{core}	heat capacity of body core [J/(m^{2}K)]
dT_{cr}	infinitesimal increment of body-core temperature [K]
Q_{shell}	heat capacity of body shell [J/(m^{2}K)]
dT_{sk}	infinitesimal increment of skin temperature [K]
V_{out}	volumetric rate of exhaled air [(m^3/s)/ m^2]
$p_{vs}(T_{cr})$	saturated water-vapor pressure at body-core temperature [K]
T_{cl}	clothing surface temperature [K]
h_{ccl}	average convective heat-transfer coefficient over clothed body-surface [W/(m^{2}K)]

Table 2.7 (b): Footnotes for Table 2.7.

*1 The value of V_{in} can be determined from the empirical formula given for human-body energy balance calculation[7] as a function of metabolic generation rate. $V_{in} \approx 1.2x10^{-6} M$.

*2 The value of V_{w-core} can be determined from the empirical formula as a function of metabolic energy generation rate and water-vapor pressure in the room space.
$V_{w-core} \approx 1.2x10^{-6} M \cdot (0.029 - 0.049x10^{-4} p_{vr})$

*3 The value of $V_{w-shell}\rho_w$ is given as the product of the skin wettedness, w [dimensionless], and the maximum evaporative potential from the skin surface to the surrounding room space, E_{max} [W/m²], divided by the latent-heat value of evaporation of liquid water at 30 °C (=2450 J/g). $V_{w-shell}\rho_w \approx w \cdot E_{max} / 2450$.

The value of w is determined by the calculation procedure given for effective temperature based on human-body energy balance by Gagge et al. [6)~8)]. The value of E_{max} can be determined as the product of evaporative heat-transfer coefficient, which is proportional to convective heat-transfer coefficient via a Lewis-relation constant, and the difference in water-vapor pressure between liquid water at skin-surface temperature and room air.

*4 The values of Q_{core} and Q_{shell} are given by the following formulae[9)].
$Q_{core} = (1-\alpha_{sk})(m_{body} / A_{body}) \cdot c_{body}$ and $Q_{shell} = \alpha_{sk}(m_{body} / A_{body}) \cdot c_{body}$, where α_{sk} is the fractional skin mass depending on the blood flow rate to the body shell (skin); m_{body} / A_{body} is the ratio of body mass to body-surface area [kg/m²]; and c_{body} is specific heat capacity of human body that is 3490 J/(kg K).

*5 The value of V_{out} is assumed to be equal to that of V_{in}.

*6 We assume that the boundary-surface temperature of human-body system is represented by the average clothing temperature. Therefore, thermal exergy outflow by radiation and convection from the human body includes the clothing temperature(see the last two columns of Table 3.2-a).) The water vapor pressure for the calculation of wet/dry exergy of humid air coming out from the human-body system should also, strictly speaking, be based on the value at the clothing surface. But, in reality, much dispersion of water vapor takes places directly at the skin surface such as forehead, neck, arms and so on. For this reason together with the avoidance of unnecessarily complicated calculation, we use water vapor pressure in the room space for the calculation of wet/dry exergy of the humid air containing the evaporated sweat (see the third row from the bottom of Table 3.2-a).).

*7 The value of h_{ccl} can be determined by one of the empirical formulae of convective heat-transfer coefficient of the human body as a whole, which is given for human-body energy balance calculation[8)].

2.3.2 Exergy in building systems

The analytical definition of physical exergy is derived applying energy and entropy balances to a combined system that consists of the system to be analysed and the surrounding environment. The analysed system can be either a control mass or control volume (i.e. a closed or open system), whereas the combined system is a control mass where only work interactions can take place across the boundary (Moran and Saphiro, 1998).

The energy supply chain of buildings is divided into subsystems (Figure 2.10). Below, the equations and exergy balances for each of the subsystems are presented, starting with the outermost subsystem, the building envelope and progressing inwards (from right to left in Figure 2.32). For each subsystem, a figure shows the boundaries for the combined and analyzed systems regarded for the exergy balance. In the following subsections the boundary of the combined system is represented as a dashed line, whereas the boundary for the analyzed system is a dotted line.

The equations for the subsystems are based on those presented in Schmidt (2004). However, they have been enhanced for a quasi-steady exergy analysis. Quasi-steady exergy assessment has shown to be a reasonable compromise between accuracy and complexity (see case studies above). Only for storage systems (e.g. storage tanks) equations for dynamic assessment are introduced.

The equations and subsystems presented here refer to the particular case of space heating in buildings. Similar calculation schemes could also be derived for other applications such as domestic hot water production or cooling applications.

2.3.2.1 Building Envelope

The net heating demand of the building, $\Phi_{h,b}$, is considered as the net energy losses. This is equivalent to the active heating demand, once internal and passive gains of the building are taken into account. It will be assumed that the heat flow takes place at the indoor air temperature, assumed as constant for each timestep as it was also assumed in the first case study ("room-air") of section 2.2.1.3.

Exergy of the energy stored in the wall construction as the heat flows through the building envelope, Exsto,env, is included in the exergy losses and thus, it is not separately evaluated in equation 2.78.

$$\mathrm{Ex}_{\mathrm{in,env}}(t_k) + \underbrace{\mathrm{Ex}_{\mathrm{out,env}}(t_k)}_{\approx 0} = \mathrm{Ex}_{\mathrm{cons,env}}(t_k) \quad (2.78)$$

With this evaluation framework, the net heat demand $\Phi_{h,b}$ is transferred to the reference environment through the building envelope, i.e. it is consumed during the process as it reaches outdoor air. The corresponding exergy is calculated according to equation 2.79 (which is equivalent to equation 2.45).

$$\mathrm{Ex}_{\mathrm{in,env}}(t_k) = \mathrm{Ex}_{\mathrm{cons}}(t_k) = \Phi_{\mathrm{h,b}}\left(1 - \frac{T_0(t_k)}{T_r(t_k)}\right) \quad (2.79)$$

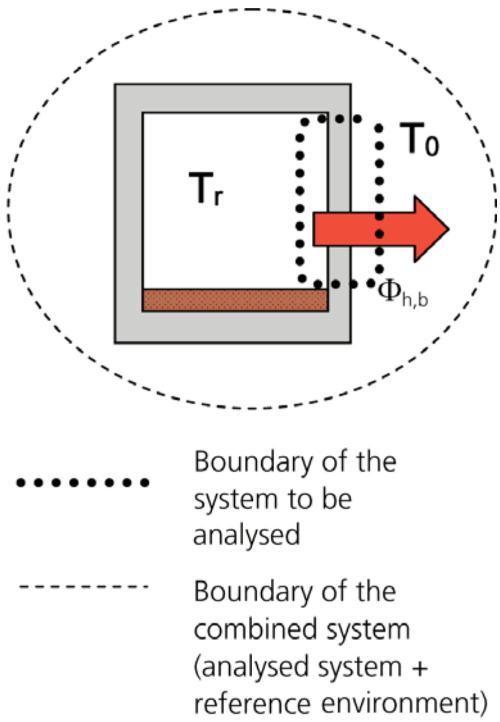


Figure 2.32: Energy flow, temperature levels and boundaries for the building envelope subsystem.

2.3.2.2 Room-air

The subsystem 'room air' is introduced to account for the exergy losses between the chosen emission system (at T_h) and the exergy demand (at T_r), since these losses should not be assigned to the emission system nor should they be assigned to the exergy demand. The energy output from the emission system equals the energy demand, but the exergy is necessarily different because of the difference in temperature allowing the heat transfer process between the heating system and the indoor air to take place.

The air temperature of the room, θ_r, is assumed to homogeneous. The surface temperature of the heater, θ_h, is estimated as the logarithmic mean temperature (LMT) of the carrier and the room air (equation 2.80), where ΔT_{LMTD} is the logarithmic mean temperature difference between the thermodynamic mean temperature of the carrier and the room air. This is a function of the inlet- and return temperatures of the carrier medium as well as the room air temperature (equation 2.81; Moran and Shapiro, 1998).

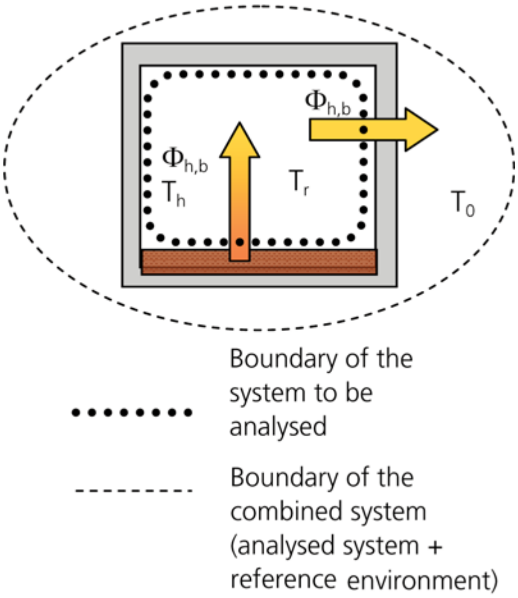


Figure 2.33: Energy flow, temperature levels and boundaries for the room air subsystem.

$$\theta_h = \Delta T_{LMTD} + \theta_r \qquad (2.80)$$

$$\Delta T_{LMTD}(t) = \frac{T_{in,ce}(t_k) - T_{ret,ce}(t_k)}{\ln\left(\frac{T_{in,ce}(t_k) - T_r(t_k)}{T_{ret,ce}(t_k) - T_r(t_k)}\right)} \qquad (2.81)$$

Equation 2.82 shows the exergy balance for the room air subsystem. Equations 2.83 and 2.84 show the exergy going into and out of the room air, respectively. In equation 2.85 these are used to calculate the exergy losses occurring during the heat transfer process. They result from the temperature difference between the heater surface and the room air temperature.

$$Ex_{in,r}(t_k) - Ex_{cons,r}(t_k) + Ex_{out,r}(t_k) = 0 \qquad (2.82)$$

$$Ex_{in,r}(t_k) = Ex_{h,b,in}(t_k) = \Phi_{h,b}(t_k) \cdot \left(1 - \frac{T_0(t_k)}{T_h(t_k)}\right) \qquad (2.83)$$

$$Ex_{out,r}(t_k) = Ex_{h,b,out}(t_k) = -\Phi_{h,b}(t_k) \cdot \left(1 - \frac{T_0(t_k)}{T_r(t_k)}\right) \qquad (2.84)$$

$$Ex_{cons,\,r}(t_k) = Ex_{h,b,in}(t_k) + Ex_{h,b,out}(t_k) = \Phi_{h,b}(t_k) \cdot T_0(t_k) \cdot \left(\frac{1}{T_r(t_k)} - \frac{1}{T_h(t_k)}\right) \qquad (2.85)$$

2.3.2.3 Emission system

The exergy balance of the emission system is:

$$Ex_{in,ce}(t_k) + Ex_{ret,ce}(t_k) + (-Ex_{h,b,in}(t_k)) = Ex_{irrev,ce}(t_k) - Ex_{ls,ce}(t_k) = Ex_{cons,ce}(t_k) \qquad (2.86)$$

Where the subindex "in" stands for inlet, "ret" for return, "h" for heating , "b" for building, "ls" for energy losses and "ce" for emissions system[13].

The additional exergy demand resulting from energy losses on the heat transfer process, $Ex_{ls,ce}$, can be added to the exergy consumption resulting from an irreversible heat transfer, $Ex_{irrev,ce}$. In this manner, the total exergy consumption in the emission system, $Ex_{cons,ce}$, can be obtained.

In equations 2.87 and 2.88 the expression for the exergy consumption is given. Equation 2.89 shows the thermal exergy demand of the emission system.

$$Ex_{cons,ce}(t_k) = Ex_{irrev,ce}(t_k) - Ex_{ls,ce}(t_k) \qquad (2.87)$$

$$Ex_{cons,ce}(t_k) = m_{w,ce}(t_k)\, c_{p,w} \left[\left(T_{in,ce}(t_k) - T_{ret,ce}(t_k)\right) - T_0(t_k) \cdot \ln\left(\frac{T_{in,ce}(t_k)}{T_{ret,ce}(t_k)}\right) \right] - \Phi_{h,b}(t_k) \cdot \left(1 - \frac{T_0(t_k)}{T_h(t_k)}\right) \qquad (2.88)$$

$$Ex_{ce}(t_k) = Ex_{h,b,in}(t_k) + Ex_{cons,ce}(t_k) = Ex_{in,ce}(t_k) + Ex_{ret,ce}(t_k) = m_{w,ce}(t_k)\, c_{p,w} \left[\left(T_{in,ce}(t_k) - T_{ret,ce}(t_k)\right) - T_0(t_k) \cdot \ln\left(\frac{T_{in,ce}(t_k)}{T_{ret,ce}(t_k)}\right) \right] \qquad (2.89)$$

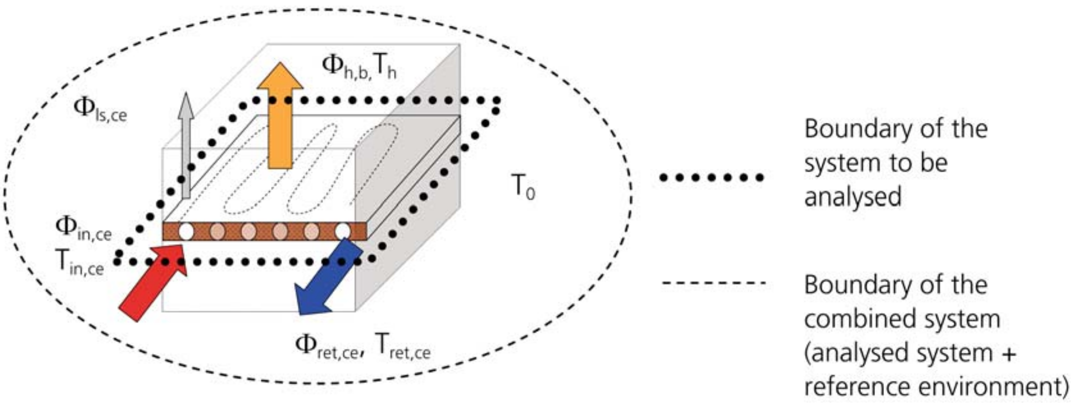


Figure 2.34: Energy flow, temperature levels and boundaries for the emission subsystem.

Case study: Thermal radiation in emission systems
In equation 2.88 the exergy output from the emission system is evaluated as a convective or conductive heat flow. However, for many space heating systems a great part of the energy flow happens through thermal radiation. As stated in section 2.1.6 exergy of thermal radiation is evaluated by equation 2.14. In order to show the influence of the different assessment of conductive, convective and radiative heat transfer for building space heating systems, a case study is presented here.

The case study consists on a multi-family dwelling with radiators which has been dynamically simulated for January in TRNSYS. Radiative and convective heat transfer terms from the radiators can be obtained separately. According to the energy simulation, 59% of the total energy output from the radiators occur due to convective heat transfer between the room-air and the radiator surface. In turn, 41% happens in the form of radiative heat transfer.

In Figure 2.35 results from the exergetic evaluation of the whole energy output from the radiators in to the room-air are shown. The dark grey curve shows the exergy output if all energy transfer is regarded as convective (named as "all convective" in the graph), i.e. using the quality factor of convective heat (eq. 2.6) for evaluating the exergy associated to the total heat transfer.

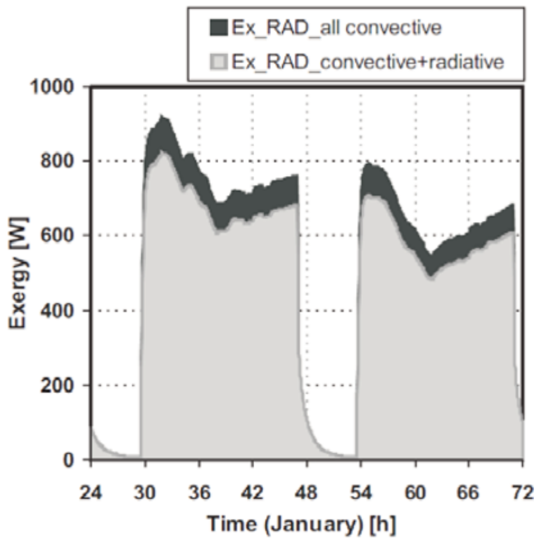


Figure 2.35: Exergy from the surface of the radiators if all energy transfer is evaluated as convective (with Carnot factor, "Ex-RAD-all convective" and evaluating the radiative and convective parts separately and correctly (with equation 1.17) and Carnot factor respectively, "Ex-RADconvective + radiative"). Results for two days are presented.

The light grey curve shows the exergy output when the corresponding radiative and convective parts of the heat transfer are evaluated as such in exergy terms (named "convective+radiative" in Figure 3.35), i.e. using the Carnot factor for evaluating the exergy of the convective part and equation 2.14 (from section 2.6.1) for the evaluation of the radiative part.

Exergy input from the radiators and into the room-air is bigger if all energy transfer is regarded as convective, i.e. using the Carnot factor. In turn, exergy input from the radiator surface into the room-air is 8% lower if the exergy from the convective and radiative parts of the heat transfer are evaluated correctly. Consequently, the bigger the radiative part on the whole heat transfer, the greater the difference between both evaluation methods.

This allows concluding that radiative heating and cooling systems may supply the same energy with lower exergy content, being thus a low exergy system.

Yet, this lower exergy input only occurs due to the bigger irreversibilities associated to the radiative heat transfer, as explained in the previous section. Energy inputs in the radiators happen mainly due to conduction from the heating fluid. Since the graph above represents the same system, the same energy and exergy is being supplied to the radiators by the heating fluid in the radiator pipes. This is shown graphically in Figure 2.36 (A), where the exergy input into the emission system is the same. As this conductive energy flux is converted into thermal radiation in the radiators and regarded as such, higher exergy losses occur within the radiators, i.e. emission subsystem in Figure 2.36 (A).

Following, the exergy output from the radiators into the room-air is lower. Subsequently, exergy losses associated to the heat transfer from the radiators to the room air, depicted in the room-air system in Figure 2.36 (B) are lower.

However, total exergy losses in the emission system as a whole remain the same, just the allocation of that losses is different, as it is shown in the right diagram on Figure 2.36 (B). In other words, from the perspective of the whole system analysis, exergy losses in the floor heating system are the same, no matter if the energy transfer to the room happens via convection or radiation. Therefore it is chosen to calculate the exergy output of the emission system using the quality factor of convective heat transfer.

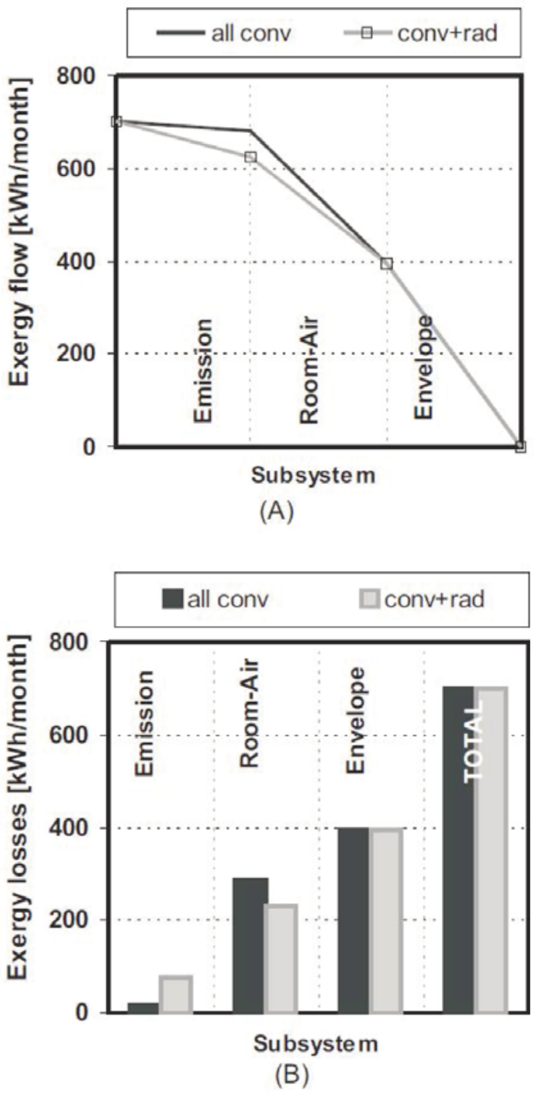


Figure 2.36: (A): Exergy flow from the radiators (emission) to the building envelope regarding all energy transfer as convective (dark grey line) and evaluating the radiative and convective parts separately (light grey line); (B): Exergy losses in the radiators, room-air and envelope subsystems, depending on whether exergy of radiative and convective heat transfer process are regarded separately.

2.3.2.4 Distribution system

For simplicity, it will be assumed that thermal energy losses in the distribution system take place only in the inlet pipes (where higher temperature levels occur). This is the approach in the Annex 49 pre-design tool for assessment of exergy flows in buildings (see 3.2). Energy transfer and exergy consumption relative to the return pipe might be calculated in a similar manner.

Exergy consumption associated with thermal energy losses are derived from the temperature drop of the fluid in the pipe, ΔTd.

Similarly as for the emission subsystem, the exergy demand 2.90 and exergy consumption 2.91 are also defined[14].

$$\mathrm{Ex}_{\mathrm{d}}(t_k) = \mathrm{Ex}_{\mathrm{cons,d}}(t_k) + \mathrm{Ex}_{\mathrm{ce}}(t_k) = \mathrm{Ex}_{\mathrm{in,d}}(t_k) + \mathrm{Ex}_{\mathrm{ret,d}}(t_k) \qquad (2.90)$$

$$\mathrm{Ex}_{cons,d}(t_k) = m_{w,d}\, c_{p,w} \left[\Delta \mathrm{T_d}(t_k) - \mathrm{T_0}(t_k) \cdot \ln\left(\frac{\mathrm{T_d}(t_k)}{\mathrm{T_d}(t_k) - \Delta \mathrm{T_d}(t_k)} \right) \right] \qquad (2.91)$$

Alternatively, thermal losses can be evaluated in the supply and returns separately using equation 2.91 as a function of the respective inlet and return temperatures in both pipes.

2.3.2.5 Storage system

The main purpose of a storage system is to achieve a time delay (or decoupling) between the energy supply and demand. The energy stored in the system is the most important variable for the definition of the storage system and exergy decrease or increase associated with temperature changes in the storage need to be regarded. Therefore a steady state or quasi-steady state analysis of the storage process cannot be performed as it would be meaningless. Consequently, the exergy associated to the storage process cannot be added to the exergy consumption as it has been done for the subsystems above.

The exergy balance for the storage system can be written as follows[15]:

$$\sum \mathrm{Ex}_{\mathrm{in,s}}(t_k) + \sum \mathrm{Ex}_{\mathrm{out,s}}(t_k) = \mathrm{Ex}_{\mathrm{cons,\,s}}(t_k) + \mathrm{Ex}_{\mathrm{sto,s}}(t_k) \qquad (2.92)$$

Where the sums are over all inputs and outputs resulting e.g from heat coming from the boiler or adding of cool water to the storage volume. The general exergy balance for the storage subsystem can also be formulated as a function of the charge and discharge processes.

$$\mathrm{Ex}_{\mathrm{ch,s}}(t_k) + \mathrm{Ex}_{\mathrm{disch,s}}(t_k) = \mathrm{Ex}_{\mathrm{cons,s}}(t_k) + \mathrm{Ex}_{\mathrm{sto,s}}(t_k) \qquad (2.93)$$

$$\mathrm{Ex}_{\mathrm{ch,s}}(t_k)=\frac{\left(\Phi_{\mathrm{ch,s}}(t_k)\right)}{\left(\mathrm{T}_{\mathrm{ch,in}}(t_k)-\mathrm{T}_{\mathrm{ch,ret}}(t_k)\right)}\left[\left(\mathrm{T}_{\mathrm{ch,in}}(t_k)-\mathrm{T}_{\mathrm{ch,ret}}(t_k)\right)-\mathrm{T}_0\cdot\ln\left(\frac{\mathrm{T}_{\mathrm{ch,in}}(t_k)}{\mathrm{T}_{\mathrm{ch,ret}}(t_k)}\right)\right]$$
$$=m_{ch,s}c_p\left[\left(\mathrm{T}_{\mathrm{ch,in}}(t_k)-\mathrm{T}_{\mathrm{ch,ret}}(t_k)\right)-\mathrm{T}_0(t_k)\cdot\ln\left(\frac{\mathrm{T}_{\mathrm{ch,in}}(t_k)}{\mathrm{T}_{\mathrm{ch,ret}}(t_k)}\right)\right] \quad (2.94)$$

$$\mathrm{Ex}_{\mathrm{disch,s}}(t_k)=\frac{\left(\Phi_{\mathrm{disch,s}}(t_k)\right)}{\left(\mathrm{T}_{\mathrm{disch,in}}(t_k)-\mathrm{T}_{\mathrm{disch,ret}}(t_k)\right)}\left[\left(\mathrm{T}_{\mathrm{disch,in}}(t_k)-\mathrm{T}_{\mathrm{disch,ret}}(t_k)\right)-\mathrm{T}_0(t_k)\cdot\ln\left(\frac{\mathrm{T}_{\mathrm{disch,in}}(t_k)}{\mathrm{T}_{\mathrm{disch,ret}}(t_k)}\right)\right]$$
$$=m_{disch,s}c_p\left[\left(\mathrm{T}_{\mathrm{disch,in}}(t_k)-\mathrm{T}_{\mathrm{disch,ret}}(t_k)\right)-\mathrm{T}_0(t_k)\cdot\ln\left(\frac{\mathrm{T}_{\mathrm{disch,in}}(t_k)}{\mathrm{T}_{\mathrm{disch,ret}}(t_k)}\right)\right] \quad (2.95)$$

The energy losses and storage process in the system are time dependent processes and result in a temperature change of the fluid in the storage tank. Consequently, the assessment of the exergy associated with the stored energy and the thermal losses has to be carried out taking into account the time dependence of the temperature.

For a given storage tank with n layers of storage fluid, the exergy stored can be written as shown in equation 2.96 The exergy stored in a well-mixed tank could be calculated with one fluid layer (n=1), whereas that of a stratified tank could be assessed by increasing the number of fluid layers. Following the sign convention expressed in section 2.1.1 the exergy stored is defined as positive if it represents an exergy input and negative otherwise.

$$\mathrm{Ex}_{\mathrm{sto,s}}(t_k)=\sum_{\mathrm{i=1}}^{\mathrm{i=n}}m_i c_{p,i}\left[\left(\mathrm{T}_{\mathrm{i,s}}(t_k)-\mathrm{T}_{\mathrm{i,s}}(t_{k-1})\right)-\mathrm{T}_0\cdot\ln\left(\frac{\mathrm{T}_{\mathrm{i,s}}(t_k)}{\mathrm{T}_{\mathrm{i,s}}(t_{k-1})}\right)\right] \quad (2.96)$$

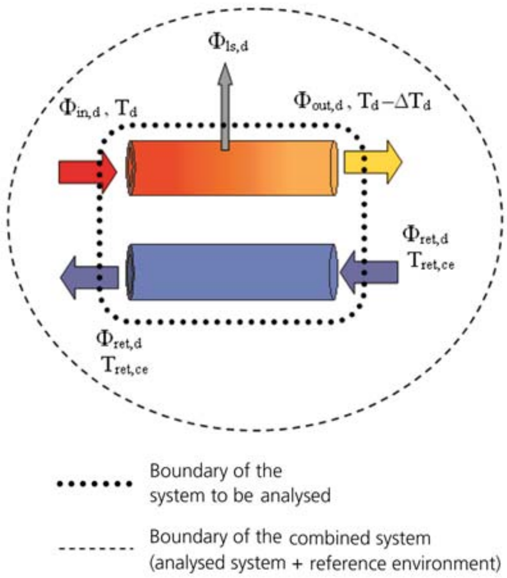


Figure 2.37: Energy flow, temperature levels and boundaries for the distribution subsystem.

As for the emission system, the total exergy consumption can be calculated by adding the exergy consumption associated to thermal energy losses from the storage tank and those corresponding to irreversibilities in the heat storage and transfer processes (equation 2.97)[16].

$$\mathrm{Ex}_{\mathrm{cons,\ s}}(t_k)=\mathrm{Ex}_{\mathrm{irrev,s}}(t_k)-\mathrm{Ex}_{\mathrm{ls,s}}(t_k) \quad (2.97)$$

Following the exergy balance in equations 2.92 and 2.93 the exergy of the thermal losses, Exls,s, is not evaluated separately, but as part of the irreversibilities or exergy consumption taking place in the storage system. An evaluation of the losses could be done as a function of the energy losses, $\Phi_{ls,s}$ and the temperature drop caused by the thermal losses in each node of the tank.

The irreversible exergy consumption occurring in the storage process can, thus, be assessed as follows:

$$\mathrm{Ex}_{\mathrm{cons,\ s}}(t_k)=\mathrm{Ex}_{\mathrm{ch,s}}(t_k)+\mathrm{Ex}_{\mathrm{disch,s}}(t_k)-\mathrm{Ex}_{\mathrm{sto,s}}(t_k) \quad (2.98)$$

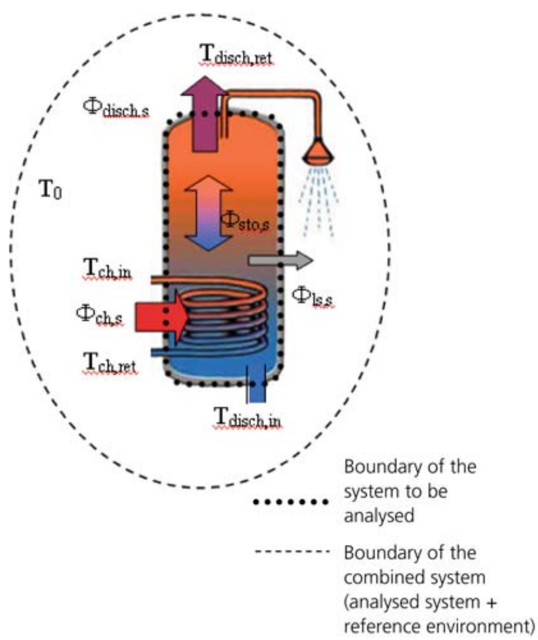


Figure 2.38: Energy flow, temperature levels and boundaries for the storage subsystem.

2.3.2.6 Generation system

This subsystem includes the exergetic performance and behaviour of the thermal energy conversion devices installed in the building. The exergy supplied by the generation subsystem has to be higher than the thermal exergy demanded by all 'earlier' subsystems, since in real systems a portion of the supplied exergy is inevitably consumed.

Boilers, heat pumps, ventilation systems, solar thermal collector fields, or any other generation units considered to supply the energy demand of the building must be regarded here.

2.3.2.7 Boiler

The thermal exergy demanded by the boiler can be calculated as a function of the amount of fuel used, Φ_g, and the corresponding quality factor associated to the energy carrier, $F_{Q,g}$, which is dependant on its chemical properties.

Assuming that no energy losses take place on the hydraulic connections between the boiler and the storage tank, the exergy consumption for the generation system is calculated as follows:

$$\mathrm{Ex}_{\mathrm{cons,g}}(t_k) = \mathrm{Ex}_{\mathrm{g}}(t_k) - \mathrm{Ex}_{\mathrm{ch,s}}(t_k) \quad (2.99)$$

The exergy input into the boiler, i.e. the exergy input into the generation subsystem, can be determined as follows:

$$Ex_{\mathrm{g}}(t_k) = \Phi_{\mathrm{g}}(t_k) \cdot \mathrm{F}_{\mathrm{q,g}} \quad (2.100)$$

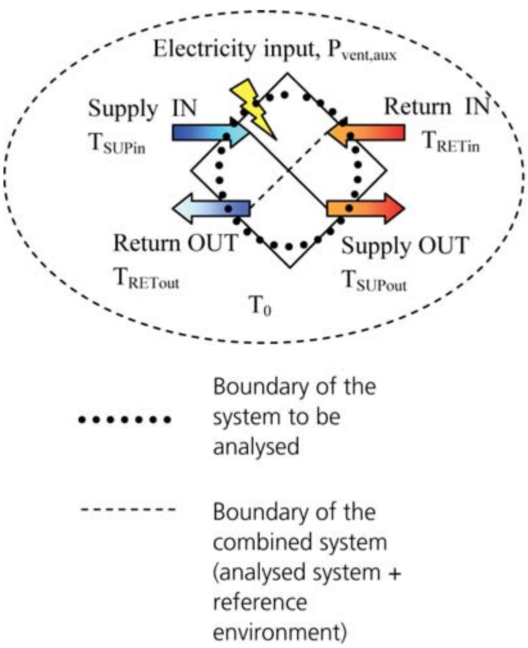


Figure 2.39: Energy flow, temperature levels and boundaries for a ventilation unit.

2.3.2.8 Ventilation system

Figure 2.39 shows the energy flows, the temperature levels and the boundaries for the closed and combined system in a ventilation unit similar to the other subsystems.

The exergy balance for the air handling unit (AHU) can be written as follows:

$$\mathrm{Ex}_{\mathrm{vent,aux}}(t_k) + \mathrm{Ex}_{\mathrm{SUPin}}(t_k) + \mathrm{Ex}_{\mathrm{RETin}}(t_k) + \mathrm{Ex}_{\mathrm{SUPout}}(t_k) + \mathrm{Ex}_{\mathrm{RETout}}(t_k) = \mathrm{Ex}_{\mathrm{cons,vent}}(t_k) \quad (2.101)$$

The exergy consumption of the ventilation unit can, therefore, be written as follows:

$$\mathrm{Ex}_{\mathrm{cons,vent}}(t_k) = \mathrm{Ex}_{\mathrm{vent,aux}}(t_k) + \mathrm{Ex}_{\mathrm{RET}}(t_k) + \mathrm{Ex}_{\mathrm{SUP}}(t_k) \quad (2.102)$$

$$= \mathrm{Ex}_{\mathrm{vent,aux}}(t_k) + \overbrace{\mathrm{Ex}_{\mathrm{SUPin}}(t_k) + \mathrm{Ex}_{\mathrm{SUPout}}(t_k)}^{\mathrm{Ex}_{\mathrm{SUP}}} + \overbrace{\mathrm{Ex}_{\mathrm{RETin}}(t_k) + \mathrm{Ex}_{\mathrm{RETout}}(t_k)}^{\mathrm{Ex}_{\mathrm{RET}}}$$

In equations 2.102 and 2.105 the term Ex_{RET} represents the exergy provided by the exhaust airflow, which in this case corresponds to exergy which is partially transmitted to the supply airflow. The term Ex_{SUP} expresses the exergy demand of the supply airflow. This last term has to be negative, since the supply air is being heated up through the heat exchanger and thus the exergy content of the supply airflow at the outlet of the heat exchanger $Ex_{SUPout}(t_k)$ is negative and higher than the exergy content of this airflow at the inlet $Ex_{SUPin}(t_k)$. Each of the terms in equation 2.102 can be calculated as follows:

$$\mathrm{Ex}_{\mathrm{vent,aux}}(t_k) = \mathrm{P}_{\mathrm{vent,aux}}(t_k) \cdot \mathrm{F}_{\mathrm{q,el}} \quad (2.103)$$

$$\mathrm{Ex}_{\mathrm{SUP}}(t_k) = \mathrm{Ex}_{\mathrm{SUPin}}(t_k) + \mathrm{Ex}_{\mathrm{SUPout}}(t_k) \quad (2.104)$$

$$= m_{SUP}(t_k)\, c_{p,air} \cdot \left((\mathrm{T}_{\mathrm{SUPin}}(t_k) - \mathrm{T}_{\mathrm{SUPout}}(t_k)) - \mathrm{T}_0(t_k) \cdot \ln\left(\frac{\mathrm{T}_{\mathrm{SUPin}}(t_k)}{\mathrm{T}_{\mathrm{SUPout}}(t_k)} \right) \right)$$

$$\mathrm{Ex}_{\mathrm{RET}}(t_k) = \mathrm{Ex}_{\mathrm{RETin}}(t_k) + \mathrm{Ex}_{\mathrm{RETout}}(t_k) \quad (2.105)$$

$$= m_{RET}(t_k)\, c_{p,air} \cdot \left((\mathrm{T}_{\mathrm{RETin}}(t_k) - \mathrm{T}_{\mathrm{RETout}}(t_k)) - \mathrm{T}_0(t_k) \cdot \ln\left(\frac{\mathrm{T}_{\mathrm{RETin}}(t_k)}{\mathrm{T}_{\mathrm{RETout}}(t_k)} \right) \right)$$

The exergy demand of the ventilation system can be calculated as follows:

$$\mathrm{Ex}_{\mathrm{vent}}(t_k) = \mathrm{Ex}_{\mathrm{in}}(t_k) + \mathrm{Ex}_{\mathrm{out}}(t_k) = \mathrm{Ex}_{\mathrm{cons,v}}(t_k) - \mathrm{Ex}_{\mathrm{SUP}}(t_k) \quad (2.106)$$

2.3.2.9 Solar thermal collectors

Solar thermal collectors are energy conversion devices which directly use the energy supplied by incident solar radiation. Considering energy processes on the planet as a whole, the earth is an open system receiving a net energy flux from the sun in the form of short-wave solar radiation. The earth emits more or less the same amount energy as long-wave thermal radiation. Other energy forms and processes present on earth are derived to a large extent from incident solar radiation, e.g. potential energy in water masses or the energy content of biomass and crops or fossil fuels. In the energy and exergy assessment of these energy resources (other than direct solar radiation), the conversion process from solar radiation into the given energy resource and its efficiency are not taken into account.

Similarly, the conversion process from solar energy to low temperature heat (in the case of solar thermal collectors) or electricity (in the case of photovoltaic systems) is not considered in the exergy analysis framework proposed here. This is also coherent with the considerations expressed in section 2.2.2.8 about solar gains through the building envelope.

Following this approach, low temperature heat obtained as output from the solar collectors is regarded as input for the storage system. Following the sign convention adopted, the exergy output from the system, Ex_{coll}, has a negative value if heat is being generated in the solar collector field.

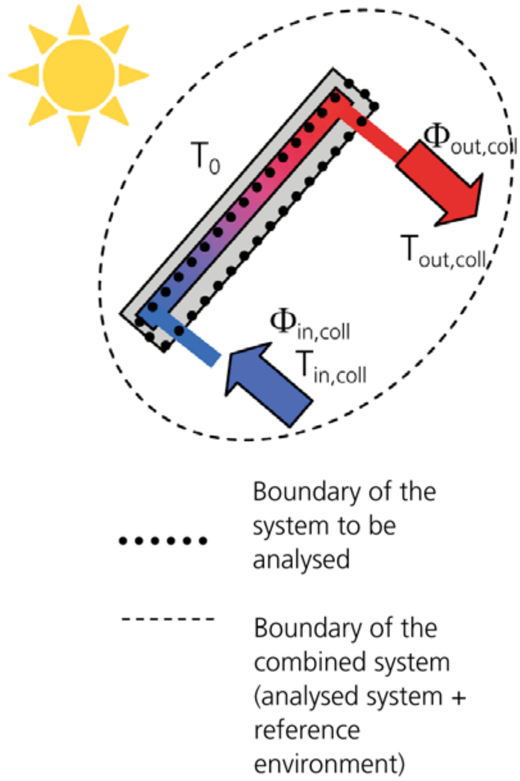


Figure 2.40: Energy flow, temperature levels and boundaries for a solar thermal collector.

$$\mathrm{Ex}_{\mathrm{coll}}(t_k) = m_{coll}(t_k)\, c_{p,coll} \cdot \left[(\mathrm{T}_{\mathrm{in,coll}}(t_k) - \mathrm{T}_{\mathrm{out,coll}}(t_k)) - \mathrm{T}_0(t_k) \cdot \ln\left(\frac{\mathrm{T}_{\mathrm{in,coll}}(t_k)}{\mathrm{T}_{\mathrm{out,coll}}(t_k)} \right) \right] \qquad (2.107)$$

Consequently, only the energy and exergy losses in the hydraulic circuit between the collector field and the storage tank are regarded as losses in the solar system. These distribution losses can be calculated similarly as in the distribution subsystem shown in section 2.3.2.4.

$$\mathrm{Ex}_{\mathrm{cons,coll}}(t_k) = -\mathrm{Ex}_{\mathrm{ls,d,coll}}(t_k) \qquad (2.108)$$

2.3.3 Add-on equations for TRNSYS

All equation expressed above have been implemented in an add-on calculator allowing quasi-steady and dynamic exergy assessment on TRNSYS. A screenshot of this calculator included in a TRNSYS model is shown in Figure 2.41. As shown, TRNSYS components (so-called "types") are used to simulate the dynamic behaviour of the energy system analysed. The energy flows and temperatures calculated by TRNSYS at every time step are given as inputs to the calculator, so that the corresponding thermal exergy flows are evaluated.

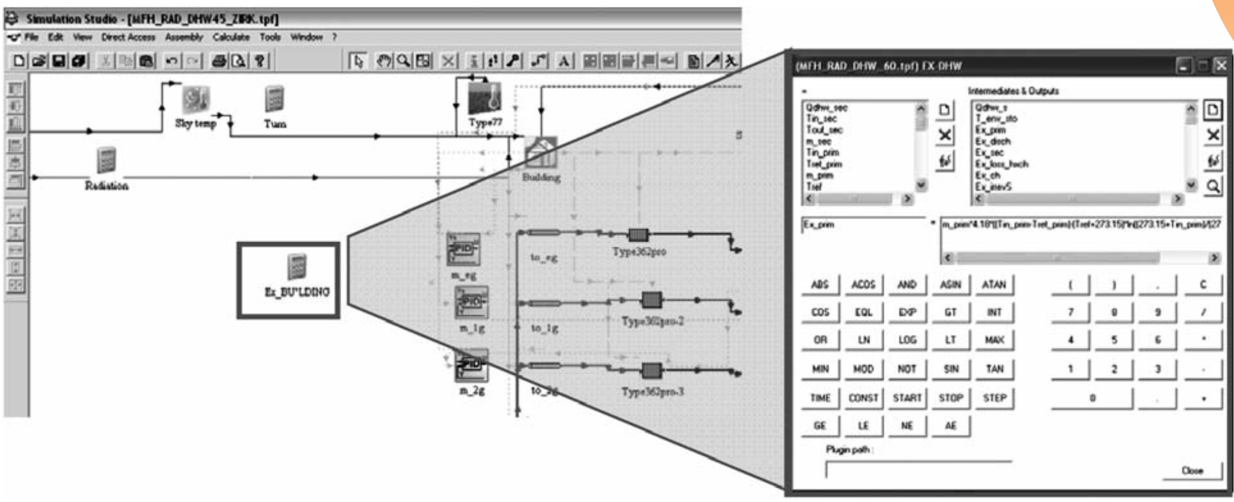


Figure 2.41: Screenshot showing an example of add-on TRNSYS equations for calculating exergy flows.

2.3.4 Exergy in community systems

Communities are complex energy systems where often a wide diversity of energy supply chains are interconnected. A great number of data with high time resolution would need to be obtained and evaluated for depicting the dynamic behaviour of a community system. A detailed and dynamic assessment of the energy and exergy flows in them would thus be very accurate, but also very time consuming. In this section some simplifications which might be used for the exergy analysis method of energy supply systems for community structures are introduced.

2.3.4.1 Dynamic or steady-state assessment

Dynamic analysis of community systems might be required if the purpose is, e.g. to optimize the performance of a system or to size the energy systems involved in an appropriate manner. For this aim, the equations presented for the analysis of building systems in the previous sections can be used to depict the dynamic exergy flows in each energy conversion step of the supply systems planned. A great number of input data with good time resolution are required for this purpose, e.g. results from dynamic energy simulations.

However, if the main aim of the analysis is to obtain a first idea of the general performance of an energy supply concept for a community preliminary steady-state assessment might be used. To assess the accurateness of simplified steady-state analysis, results with such an approach are compared to results from dynamic analysis for one of the case studies presented in chapter 7. The case study of Oberzwehren (Germany) is used for this purpose (see 7.5).

The case study corresponds to a small neighbourhood whose space heating (SH) and domestic hot water (DHW) demands are supplied with a low-temperature district heating system. District heat corresponds to waste heat and is supplied to the hydraulic distribution network inside the neighbourhood by means of a centralized heat exchanger. The buildings and energy supply systems, i.e. heat exchangers, pumps and thermal losses in the hydraulic network have been dynamically simulated with TRNSYS. A time step of 3 minutes is used for the simulations. Following the simplified input-output approach mentioned in the previous section, the exergy associated to main inputs into the system are analysed. These energy inputs are the heat input from the primary side of the district heating heat exchanger, pumping energy in the secondary sides and auxiliary energy to power the back-up electric heater for DHW supply. Since, it is a waste heat district heating system, the exergy associated to the primary side heat transfer from the heat exchanger can be evaluated as a function of its inlet and return temperatures. If in turn, it would be heat from a heat plant, the quality factor of the fuel used to supply the heat would need to be assessed.

Equation 2.109 shows the expression for the dynamic exergy efficiency.

$$\psi_{DH,dyn} = \frac{\sum_{k=1}^{k=N} Ex_{dem,SH}(t_k) + \sum_{k=1}^{k=N} Ex_{dem,DHW}(t_k)}{\sum_{k=1}^{k=N} Ex_{in,DH}(t_k) + \sum_{k=1}^{k=N} P_{pumps}(t_k) + \sum_{k=1}^{k=N} P_{el,heater}(t_k)} \qquad (2.109)$$

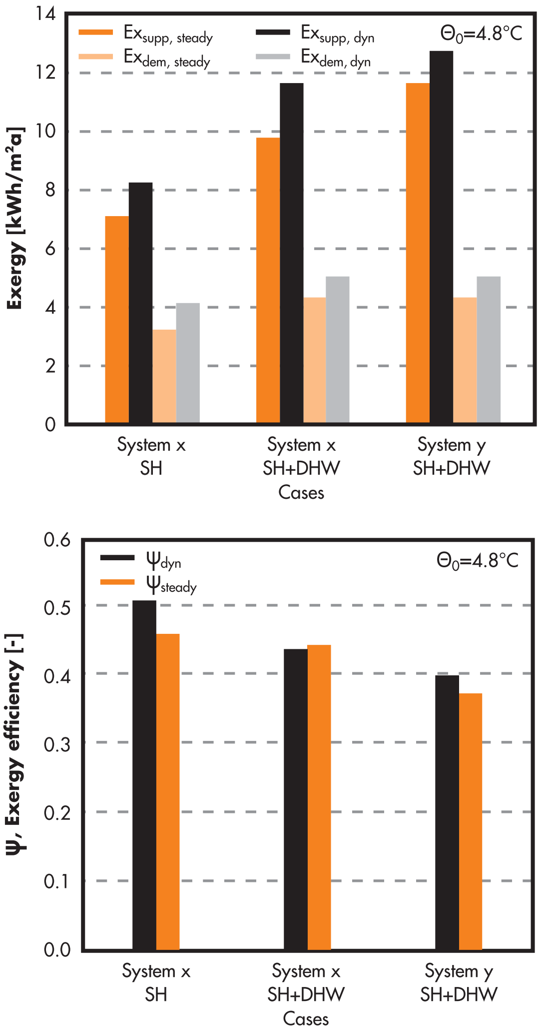


Figure 2.42: (a): Exergy demand and supply following dynamic and steady-state assessment methods for two different hydraulic configurations (system x and system y) as well as only for SH and for combined SH and DHW supply; (b): Seasonal dynamic exergy efficiency and steady-state exergy efficiency calculated assuming design operating conditions and yearly energy demands..

Equation 2.110 shows the expression for the steady-state assessment of the exergy efficiency. The expressions for steady-state assessment of the exergy supplied and demanded can be found in the denominator and numerator respectively. Pumping energy and electricity for the back-up electric heater represent a marginal input in the systems analyzed as compared to the heat input from the district heating system and thus, are disregarded in steady-state assessment. Average outdoor air temperature during the heating period is used here as reference temperature for exergy analysis. Estimated yearly energy demands for SH and DHW are used in combination with design conditions for the supply systems chosen, i.e. design inlet and return temperatures and mass flows for the district heating heat exchanger.

Figure 2.42 (a) shows results for the exergy supply and demand following a dynamic and steady-state assessment. Figure 2.42 (b) shows the exergy efficiencies for both analysis methods.

With the conditions considered here for stationary analysis, steady-state evaluation gives a reasonably accurate first estimation on the trend of the exergy efficiency of the system. Agreement between steady-state and dynamic exergy assessments is better for the seasonal exergy efficiency. Mismatching between the seasonal exergy efficiency for different configurations of the supply systems are lower than 10%. In turn, differences for the exergy demanded and supplied with both assessment approaches (dynamic and steady-state) are higher, amounting as much as 22%. The trend, however, is similar for both assessment methods. It can be concluded that steady-state exergy analysis as performed here gives correct insight on the trend of the exergy performance for different systems and can be therefore used for comparing them. Absolute values of the exergy performance obtained with this simplified evaluation method, however, are not accurate.

$$\psi_{DH,steady} = \frac{Ex_{dem,SH,steady}+Ex_{dem,DHW,steady}}{Ex_{in,DH,steady}}$$

$$= \frac{Q_{SH,annual}\cdot\left(1-\frac{\overline{T_{0,HP}}}{T_r}\right)+\frac{Q_{dem,DHW,annual}}{(T_{dem,DHW}-T_{net})}\cdot\left[(T_{dem,DHW}-T_{net})-\overline{T_{0,HP}}\cdot\ln\left(\frac{T_{dem,DHW}}{T_{net}}\right)\right]}{\dot{m}_{prim,DH,design}\cdot c_p\left[(T_{in,prim,DH,design}-T_{ret,prim,DH,design})-\overline{T_{0,HP}}\cdot\ln\left(\frac{T_{in,prim,DH,design}}{T_{ret,prim,DH,design}}\right)\right]} \qquad (2.110)$$

2.3.4.2 Simplified input-output approach for communities

As shown above, simplified steady-state analyses are suitable to give an idea of the exergy behaviour of community supply systems. Energy systems in communities enclose often a great diversity of energy supply systems. A detailed assessment of every energy conversion step in the different supply systems involved would require a great number of data and time consuming analysis. As a first step, communities can be depicted as a set of demands to be provided, with their corresponding quality level (i.e. exergy content associated to them) and a set of possible energy supply sources available. This simplified approach allows depicting on a relatively simple way the suitability of different supply options by assessing the matching level between the demands and the sources used.

In Figure 2.43 some possible energy sources and energy uses present in a community system are classified according to their quality level (i.e. exergy content). Ideally, high quality sources are used only to provide high quality applications whereas low quality sources should be used for low quality applications.

2.4 Main conclusions

In this chapter the main fundamentals for performing exergy analysis in buildings have been introduced and discussed. Different methods for exergy analysis have also been discussed and the general equations for several building subsystems have been presented. The main conclusions obtained regarding the method for exergy analysis in buildings are:

- Outdoor air surrounding the building is an appropriate reference environment for exergy analysis. Dynamic values of the outdoor air temperature can be used to describe the thermal reference environment for dynamic and quasi-steady state exergy calculations. For first estimations with steady state exergy analysis the average temperature during the heating season can be taken.

- Quasi-steady state exergy analysis represents a reasonable compromise between accurateness and complexity. It can be applied for exergy calculations in buildings aiming at analyzing the performance of whole building systems. However, if the main goal of the analysis is to optimize or study the performance of storage components dynamic assessments need to be used.

- Steady-state exergy analysis can be used for first estimations on the performance of building systems and communities. A first comparison on the performance of different supply systems can be carried out by means of these simplified analysis. However, for an accurate comparison of different building energy supply systems quasi-steady state or dynamic exergy analysis are required.

- For estimating the exergy demand of a building the simplified approach introduced in section 2.2.2 can be used if the performance of complete building supply systems is under study. If in turn, the main focus of the analysis is to study or investigate merely the performance of different emission systems or building constructions, the detailed exergy demand calculation method shall be applied.

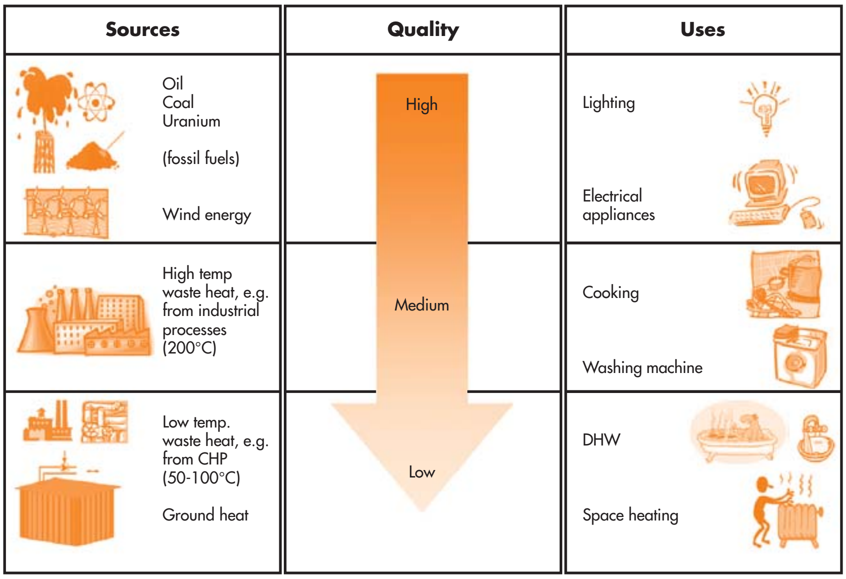


Figure 2.43: Simple classification of energy sources and uses (i.e. demands) in a community according to their quality level.

[2] *"Primary energy transformation" and "Generation" subsystems referred here corresponds to the modular method for exergy analysis developed by Schmidt (2004).*

[3] *The quality factor of 0.94 is referred to a reference temperature of 25°C. However, the variation of this value due to deviations in the reference environment chosen are expected to be lower than the uncertainty in the calculated value. In consequence, here the same value is assumed for all reference environments chosen.*

[4] *Directly available in the sense that if a heating load is present, i.e. $T_{indoors}$ < 20°C, having an undisturbed ground temperature greater than 20°C would not reduce directly the heating load unless a suitable energy system (e.g. ground heat exchanger) is installed.*

[5] *On the contrary as the undisturbed ground temperature, if a heating load is present, i.e. $T_{indoors}$ <20°C, having an outdoor air temperature greater than 20°C would directly reduce the heating load (by e.g. opening the window).*

[6] *Quality factors for the solar thermal system are referred to the heat output from the solar collectors. The conversion of solar radiation in low temperature heat is disregarded.*

[7] *A detailed description of the exergy balances of the "room-air" subsystem can be found in section 2.3.2.2.*

[8] Q_{env} *has a negative value, since it is an energy output from the system.*

[9] *For a detailed calculation of the different flows existing textbooks on building physics can be consulted.*

[10] *In this case the energy flow following the ventilation air already appearing in the energy balance does also represent an output of unwanted exergy (and is thus a desired output) and could be seen additional as "harvestable" exergy.*

[11] *Of course it has to be stated that this considers the ideal demand (as in minimum amount of work required). The exergy used will depend on the systems applied, but this is the case for both the simplified and the detailed calculation methods.*

[12] *(If the solar temperature of 6000 K would be taken, as is sometimes suggested, this would mean that also in a cooling case the solar gains represent an exergy input. From the zone this is not a correct representation, since the exergy of the zone is decreased. This means the potential work of the sun must can be accounted for elsewhere, and it is not possible to evaluate both "warm exergy" and "cool exergy" entering a zone at the same time.)*

[13] $\Phi_{ls,ce}$ *and* $Ex_{ls,ce}$ *are considered as negative (energy and exergy outputs from the emission system).*

[14] $Ex_{dem,ce}$ *has already been defined as positive in the emission system. Thus, to be consistent for both subsystems, is kept as positive for the distribution system. Otherwise, it could be written:* $\mathrm{Ex}_{dem,d}(t) = \mathrm{Ex}_{cons,d}(t) - (-\mathrm{Ex}_{dem,ce}(t))$.

[15] *Outputs, i.e. discharging processes, are regarded as negative.*

[16] $\Phi_{ls,s}$ *and* $Ex_{ls,s}$ *are considered as negative (energy and exergy outputs from the storage system).*

3. TOOLS FOR EXERGY ANALYSIS

In order to promote the use of the exergy concept among building planners and decision makers a variety of software tools have been developed within ECBCS Annex 49. These have different levels of complexity and can be used in various applications. These tools are at the forefront of the use of exergy in the building sector. They provide a unique viewpoint that simple analysis based on energy balances alone might overlook. Many designers may be unaware or incapable of performing an analysis that considers exergy flows through buildings. These tools provide designers with a range of options to produce results pertaining to the exergetic performance of a particular design. These can lead the designer to subsequent optimizations that would otherwise not be applied.

3.1 Overview of developed Tools

The tools developed have a wide range of applications and are focused on the analysis of different parts of energy supply systems in buildings. Three MS Excel based tools are available: Annex 49 predesing tool for exergy analysis of building systems, SEPE performing exergy analysis of system components and Cascadia which can be used for exergy analysis of community systems. The exergy calculations have also been implanted into a Building Information Modeling (BIM) tool, allowing energy and exergy calculations for the three-dimensional computer designs of architects. Beyond system analysis, another MS Excel software tool has been developed to improve comfort analysis, which models the exergy of the human body. Finally a graphical tool has been created, which acts as a decision tree to provide a very simple guide for owners and designers in the selection and integration of low exergy building cooling systems. A summary of the tool applications is given in Table 3.1

3.2 Annex 49 pre-design Tool

The Annex 49 pre-design tool is a MS Excel-based calculation tool intended to analyze energy supply systems in buildings. It is based on a simplified steady-state approach for energy and exergy analysis. The tool allows to depict the overall performance of energy supply systems in buildings, as well as the exergy performance of single components of such supply systems (i.e. boiler, solar collectors, floor heating systems…).

This tool is based on the German energy saving Standard (EnEV, 2007), which targets the limitation of the energy consumption of buildings. Thereby, the field of application is focusing mainly on buildings with normal and low internal temperatures respectively, as e.g. residential buildings, day-care facilities for children and office buildings.

The objective was to develop a simple and transparent tool which is easy to understand and comprehensible for its users, such as architects and construction engineers. Further assumptions have been made to compose exergy analysis as clearly as possible, and to limit the required input data.

This tool is based on the MS Excel tool developed within IEA ECBCS Annex 37. Main changes introduced in the actual Annex 49 pre-design tool are:

- Two different energy sources, or energy supply systems for DHW and space heating demands can be combined, e.g. solar thermal collectors and heat pumps, boilers, etc…
- Renewable energy flows are accounted for, both in energy and exergy terms, in the generation and primary energy transformation subsystems.
- Renewable and fossil energy and exergy flows are regarded separately, allowing good traceability of different energy sources on the energy supply chain.

Table 3.1: Summary of tools for exergy analysis in the built environment developed during the Annex 49 project.

Tool	Ideal User	Calc Level	Interface	Programming	Availability	Manual	Repository
Annex 49 pre-design tool	Engineer/ Architect	System/Building	Excel	BASIC	Public	Yes	Annex 49
Cascadia	Eng./Planer	Community	Excel	BASIC	Public	No	Annex 49
SEPE	Engineer	System/ Component	Excel	BASIC	Public	Yes	Annex 49
DPV	Arch./Eng.	Building	GUI	C	Private	Yes (DE)	Keoto
Human Body	Engineer	Occupant	Excel (GUI)	BASIC (FORTRAN)	Public	Yes	Annex 49
Decision Tree	Owner/Planer	System/Building	Graphical	--	Public	Yes	Swiss BfE

All relevant building data as well as heating ventilation and air conditioning (HVAC) systems can be selected directly by the user on the first page. Results are also presented graphically at the end of the first page. Main assumptions are summarised in tables on further pages. The analysis considers all steps of the energy chain – from the primary energy source to the building and the environment (i.e. the ambient climate).

Potential uses of this tool are for studies of, e.g., effects of improving the building envelope compared to improving the building equipment, or system flexibility and the possible integration of renewable energy sources within the building system.

3.2.1 Tool description

Based on the steady-state heat demand, an exergy analysis is performed. It is calculated for a design point for outdoor/indoor conditions, radiation, internal gains and air exchange rate defined by the user. Due to the inaccuracies of performing an annual exergy analysis based on quasi steady-state conditions, and in order to avoid misinterpretation of the results, isolated steady-state analysis has been preferred.

Through the separate analysis of renewable and fossil energy flows an exact determination of the pure-renewable share is possible. A further advantage of this structure is the separate examination of the domestic hot water production. Following, the clearness of the whole system is improved.

The tool is divided into the blocks and subsystems illustrated in Figure 2.10 (in direction of the energy flow), following the same structure used for developing the method for exergy analysis presented in chapter 2.

1. Primary energy transformation:
Energy sources found in nature for their exploitation are regarded as primary energy flows. Transport and transformation processes required to make these sources usable to buildings are considered within this first section. Furthermore, it is possible to take the climatic aspect of the energy usage (as CO2 emissions) into consideration within this analysis because the sources of renewable and fossil energies are dealt separately. This is important for the power generation and distribution since high losses arise there.

2. Generation:
Final energy enters the building envelope as final energy. The energy carrier (e.g. oil, natural gas or electricity) has to be transformed into heat for the rooms. This is normally carried out through 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. Losses within the storage system have to be considered and, if required, a need of additional energy for the recirculation.

4. Distribution:
The heat offered 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 and 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 to heat it up. Heat losses can appear depending on the system design and 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.

3.2.2 Layout of the tool

The tool is divided into 10 Excel worksheets within the Excel spreadsheet tool. The first worksheet, which is the pre-design sheet, is the most significant to the user. It is where all the building parameters are input and where the energy and exergy analysis is implemented. It is also where the output graphs and results are displayed. It is described in detail in the next section.

The other sheets include a General Values sheet where the configuration of all calculated values have been set and where the balancing of the energy and exergy take place. The sheets for the Values Generation-Conversion, Storage, Distribution, Emission, and DHW contain the necessary system parameters such as primary energy factors, efficiencies, design temperatures, etc. for the calculations in these various subsystems. The Interpretation sheet classifies the results of the calculations between the subsystems from generation until the building envelope. The Efficiencies sheet contains the list of parameters for characterizing the energy and exergy performance of the studied object. The Factors sheet provides a summary list with the main factors chosen or assumed for the calculation of the studied object.

3.2.3 Inputs

3.2.3.1 Pre-design sheet

The pre-design sheet illustrates the input formula as well as the evaluation for the user. The user inputs are filled in the yellow cells of the spreadsheet. Alternatively, there are pre-loaded objects that can be selected by pressing the grey buttons at the top of the sheet.

The pre-design sheet is divided into six sections for the input and calculation of parameters as shown in the following table:

Table 3.2: Sections of the pre-design sheet of the Excel Tool.

Section 1:	Project data, boundary conditions: Project data and boundary conditions are requested for the analysis (volume, area and U-values)
Section 2:	Heat losses: Identification of heat losses due to transmission through the building envelope and ventilation
Section 3&4:	Heat gains and other uses: Identification of the solar and internal heat gains which will be subsequently subtracted from the heat losses
Section 5:	Heat demand: The heat balance is specified based on the first law of thermodynamics where offsetting gains against losses
Section 6:	Heat production and emission: Choosing of systems engineering as well as detailed input for generation, storage, distribution, emission and energy sources (renewable, fossil)
Section 7:	Results of exergy calculation: Extensive exergy analysis

3.2.3.2 Project data, boundary conditions

The first section of the pre-design sheet deals with the project data and boundary conditions, including the heated building volume V in m^3, the indoor air temperature, the outdoor air temperature and net floor area Anet in m^2. The ambient air temperature desired is also introduced here. It represents the reference temperature for exergy analysis and determines energy losses, and thereby, energy demand of the building under analysis.

3.2.3.3 Heat losses

To calculate the heat requirement of a building the heat loss has to be calculated first. Thereby, the heat loss through the building envelope is subdivided into transmission losses and ventilation losses.

The calculation of the transmission losses due to transmission through walls, windows, doors, floors and ceilings is carried out based on the German regulation on energy saving (EnEV, 2007). The area and thermal transmittance of all external surfaces must be defined for this calculation. The usage of temperature correction factors replaces the extensive individual calculation of the heat transfer from the heated to unheated room and outside respectively. These temperature factors are acceptable for a first estimation of the energy demands of buildings. Also thermal bridges are disregarded.

The ventilation heat loss is calculated directly and easily according to DIN EN 832 (2003) and DIN V 4108-6 (2002) respectively. The user enters the air exchange rate nd. If a mechanical balanced heating system with heat recovery was chosen the heat exchanger efficiency ηV has to be entered too.

3.2.3.4 Heat gains and other uses

The heat gains have to be considered within this balance similar to the losses. They are subdivided into solar heat gains and internal heat gains.

The user has to specify the reducing factor for the window frame fraction, define the window area and operative total transmittance. The solar irradiation is given, but can be adjusted

The internal heat gains in residential buildings differ from the internal gains in office and administration buildings. The internal loads are higher in office buildings because of the office equipment. Hence, the number of occupants, specific heat rate per occupant, and specific internal gains of equipment have to be entered.

Other uses, as, for example, from artificial lighting or ventilation can be considered by manual input. Lighting is considered to cause extra internal gains.

It is assumed that the electricity demand for lighting turns into internal heat loads inside the building, thus contributing to the internal gains in addition to occupants and equipment.

3.2.3.5 Heat demand

All heat flows, i.e. transmission and ventilation losses as well as the internal and solar gains are incorporated in the energy balance by applying the first law of thermodynamics:

Heat demand = sum of heat losses - sum of heat gains
= (transmission and ventilation) - (solar, equipment, occupants and lighting)

$$\Phi_h = \Phi_{trans} + \Phi_{vent,ls} - \Phi_{sol} + \Phi_{int,eqp} + \Phi_{int,occ} + \Phi_{int,L} \quad (3.1)$$

3.2.3.6 Heat Supply and Emission

This section determines the characteristic data for the heating system and their sub-systems. This section is structured in to include Generation, Storage, Distribution Systems, Emission system, and domestic hot water (DHW) production.

For generation, the user can select from 14 different energy supply systems. These range from standard boiler to district heat to various types of solar collectors. It is possible to define only one source (e.g. standard boiler) or two sources (e.g. boiler combined with solar vacuum tube collectors). In case a combination of two energy sources are chosen, the share of each system in providing the whole energy demand also has to be defined. For each energy source, the primary energy factor for the primary energy conversion and the associated quality factor, required for the exergy analysis, are provided. In order to backtrack renewable and fossil energy flows separately, primary energy and quality factors are defined separately for the renewable and fossil parts of the energy carrier and flow chosen. The thermal efficiency, primary fossil/renewable energy factor, quality fossil/renewable factor, maximum supply temperature, auxiliary energy, specific CO_2 emissions, and source fraction are produced based on the system selection in this section.

An additional parameter is defined if a heat pump is used as generation system, which allows evaluation of the energy collected by the heat pump from the environment (e.g. ground source heat, air heat, etc.). It is included in the renewable energy flows in the system and a quality factor, depending on the temperature level of the regarded heat source, is defined and applied to it.

After generation, the storage option must be chosen. The user can decide between there being no storage in the system or a small/day storage. The heat storage system is characterised by 3 parameters. These parameters are the heat loss and efficiency of the storage and the auxiliary energy used.

The user can also select four different parameters describing the distribution system: boiler position, insulation, design temperature and finally temperature drop. The boiler position can be inside or outside. The insulation can be none, bad, or good.

The design temperature can be low (<35°C), middle (<50°C) or High (other). The temperature drop can be low (<5K), middle (<10K) or high (other). The distribution system is also characterised by the heat loss and efficiency parameter and by its auxiliary energy demand.

Sixteen different options can be chosen as emission system: floor heating, wall heating, radiators, air heating/cooling, ceiling heating, slab heating/cooling, free cooling/ventilation, high temperature (HT) radiators (with supply/return temperatures of either 90/70, 55/45, or 35/28), low temperature (LT) radiators, low temperature wall heating, radiating panel, slab and floor heating, or direct electric heating. Each system is described in the tool by their inlet temperature, return temperature, auxiliary energy demand, maximum heat emission, and heat loss/efficiency.

Finally, the user must define the DHW supply parameters. The user can select between domestic hot water production with and without recirculation, and DHW supply from a series of predefined options. The DHW parameters are the demand, supply temperature, efficiency of hot water heating system, primary energy factor fossil, primary energy factor renewable, fossil quality factor, renewable quality factor, and the source fraction.

For DHW, a separation of the sources can take place as in the space heating generation subsystem. The warm water production can result from a fossil heating facility or from a combination of a fossil heating facility with a solar collector. The share of the renewable source has to be defined within a yellow cell too.

3.2.4 Exergy calculations

The exergy method presented in section 2.3.2 of the previous chapter is applied for steady-state conditions in the tool. The calculations are carried out in the direction of the development of demand, as illustrated in Figure 2.10. The demand of the each subsystem (i.e. its input) has to be supplied by the previous one, i.e. is the output of the previous subsystem. The difference between the input and output in each system represents its exergy losses. Detailed equations used for calculating the exergy behaviour of each subsystem can be found in chapter 2. All equations are stated analytically in the pre-design sheet. In this way, transparency is ensured and the exergy calculations can be completely understood and followed by the user.

3.2.5 System check

The consistency of the results is checked automatically. Three diverse tests are implemented:

1. If the calculated heat demand is higher than the possible maximum heat emission of the emission subsystem, a message will be shown. New and modern buildings with advanced emission systems, such as thermal active building components, require an adequate building envelope due to their limited maximum heating power. Therefore, 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 exceeded the subsequent error message will be announced:

   $$\Phi_h > p_{ce,h,\max} \cdot A_{net} \qquad (3.2)$$

   "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 prove if 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 has to be higher than the necessary inlet temperature of the emission system.
   If the following condition is exceeded the subsequent error message will be announced:

   $$\theta_{SUP,\max} < \theta_{in} \qquad (3.3)$$

   "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 subsequent error message will be shown:

   $$\left(\Phi_{trans} + \Phi_{Vent,Is}\right) < \left(\Phi_{sol} + \Phi_{\mathrm{int},,occ} + \Phi_{in,eqp} + \Phi_{\mathrm{int},L}\right)$$
   $$\text{or} \quad \Phi_h < 0 \qquad (3.3)$$

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

4. 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"

3.2.6 Output and Analysis

After all data are entered for the investigated building the results are recapitulated in Figure 3.1. The overall exergy efficiency for the energy supply, as well as exergy expenditure figures for the generation and emission systems are stated. The quality factor of the energy demand, stated as exergy expenditure figure (see 5.1.3), is also shown.

The exergy flexibility factor displays the exergetic load of the room-air as compared to that provided by the emission system. Higher values indicate that the chosen emission system provides the given demand without high exergy losses, i.e. with a lower temperature level. This corresponds to a more flexible system, which, due to the low temperature levels required, can be supplied with a wider variety of energy sources (therefore being more flexible).

3.2.6.1 Energy and Exergy Flows

The calculated energy and exergy flows are illustrated in two diagrams. Here, a separation occurs for the heating system and the DHW production.

Figure 3.2 shows the energy and exergy flows of the heating system, divided in their renewable and fossil components. The results are shown as demand and loss through the individual components. In Figure 3.2 it is obvious to see where high losses (i.e. steep lines) appear and possible points for an additional efficiency increase can be achieved. From the storage onwards no statement can be given anymore on whether the energy is from a renewable or fossil nature. Solar gains, e.g. trough the window are displayed through the increase in the room air system both in energy (dashed black line) and exergy terms (continuous black line). Due to these gains more energy is finally available for the room as without internal and solar gains.

Energy and exergy flows for DHW supply are displayed similarly on a separate diagram.

Characteristic Exergy Values		
Overall Exergy Efficiencies [-]		
$\psi_{o,prim} = Ex_{room}/Ex_{in,Tot}$;	$\psi_{o,prim}$ =	**0.018**
Exergy expenditure figures (Space heating only)		
$\varepsilon_{gen} = (Ex_{gen,fos,S1}+Ex_{gen,rene,S1}+Ex_{gen,fos,S2}+Ex_{gen,rene,S2}+P_{aux,gen,S1}+P_{aux,gen,S2})/\Phi_S$;	ε_{gen} =	**1.020**
$\varepsilon_{em} = (Ex_{em}+P_{aux,em})/\Phi_H$;	ε_{em} =	**1.053**
$\varepsilon_{demand} = F_{q,room} = 1-T_e/T_{in}$;	ε_{demand} =	**0.071**

Characteristic Energy Values		
Overall Energy Efficiencies [-]		
$\eta_{o,prim} = \Phi_H/En_{in,Tot}$;	$\eta_{o,prim}$ =	0.254

Results in key figures	total	per Area	per Volume
Energy input (fossil & renewable energy+internal and solar gains+auxillary power)	9277.18 W	83.73 W/m²	21.71 W/m³
Total energy input (Energy input + ventilation + lighting + DHW)	10762.29 W	83.73 W/m²	25.19 W/m³
Exergy input (fossil & renewable energy+internal and solar gains+auxillary power)	9277.18 W	83.73 W/m²	21.71 W/m³
Total exergy input (Energy input + ventilation + lighting + DHW)	10762.29 W	83.73 W/m²	25.19 W/m³
Energy demand of envelope (heat demand + internal and solar gains)	4316.57 W	38.96 W/m²	10.10 W/m³
Total exergy system efficiency (Ex. demand Room+DHW / total exergy input), $\psi_{o,p}$	2.06%		
Exergy flexibility factor (exergy load room-air / exergy load emission)	6.78%		

Figure 3.1: Summary of energy and exergy performance figures.

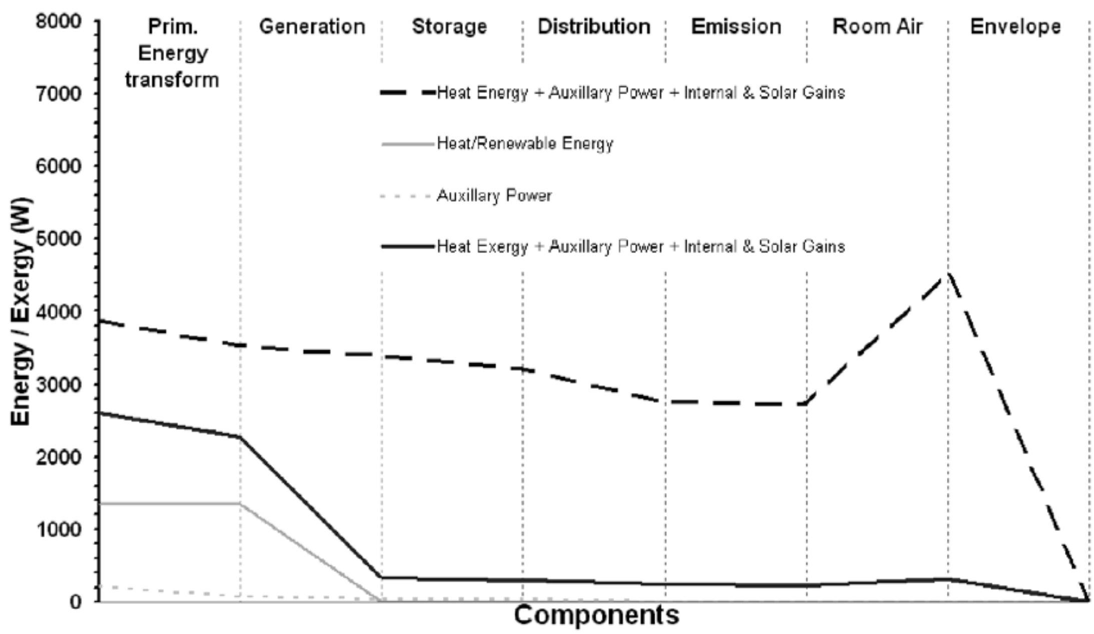


Figure 3.2: Exergy and energy flows through components for space heating supply.

3.2.6.2 Energy and Exergy Losses

In Figure 3.3 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 are regarded and contribute to compensate the total transmission and ventilation losses.

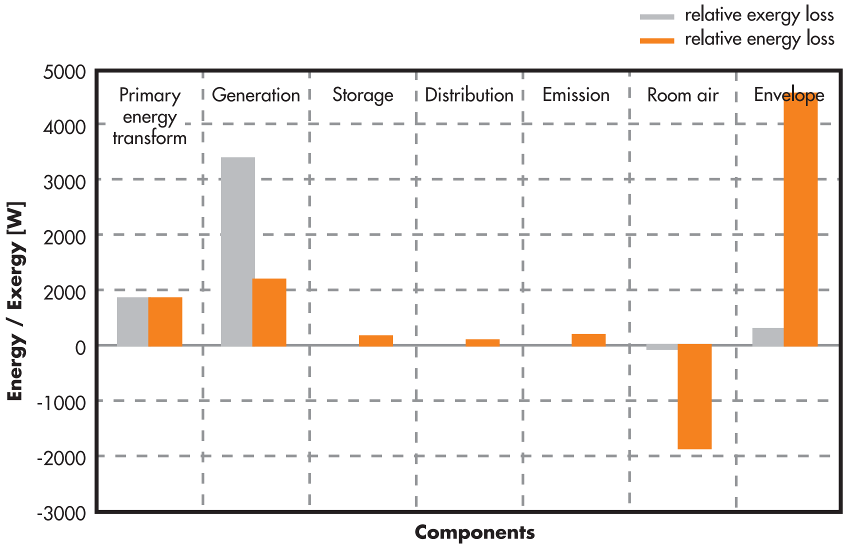


Figure 3.3: Exergy and energy losses in each subsystem of the energy supply chain.

3.2.6.3 Energy and exergy building inputs and outputs

Figure 3.4 and Figure 3.5 show the energy and exergy supply compared to the energy and exergy demand. According to the first law of thermodynamics the coverage has to be equal to the demand because no energy can be destroyed.

3.3 Cascadia

The MS Excel-based tool "Cascadia" intends to provide insight about the exergy performance of different energy supply systems for communities. The tool aims thereby at introducing the exergy concept to municipal planners and decision makers, so that main conclusions from exergy analysis on a community level can be integrated on the design process.

3.3.1 Extension into Communities

Cascadia is based on the calculation method implemented in the spreadsheet Annex 49 pre-design tool. While the model in the pre-design tool is focused upon individual building components, radiators, heat transfer equipment, etc, the model used in

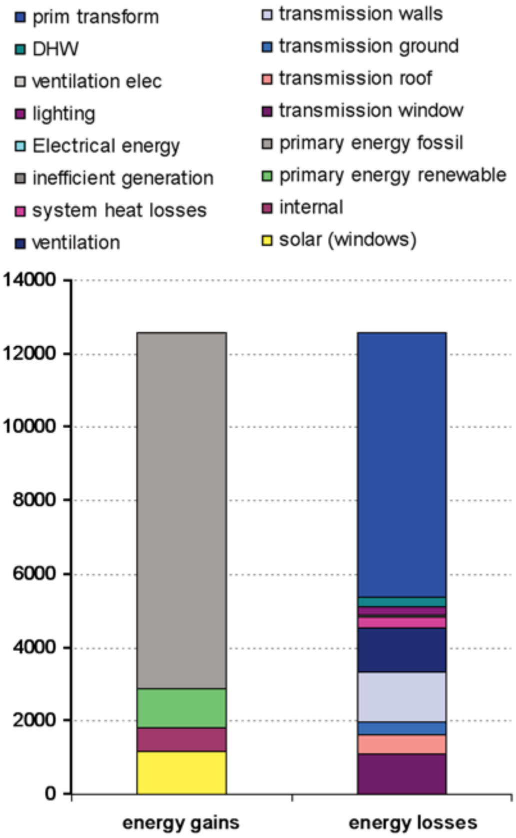


Figure 3.4: Energy gains and losses.

In Figure 3.5 the exergy demanded and supplied in each subsystem is shown. The balance between both should always be zero.

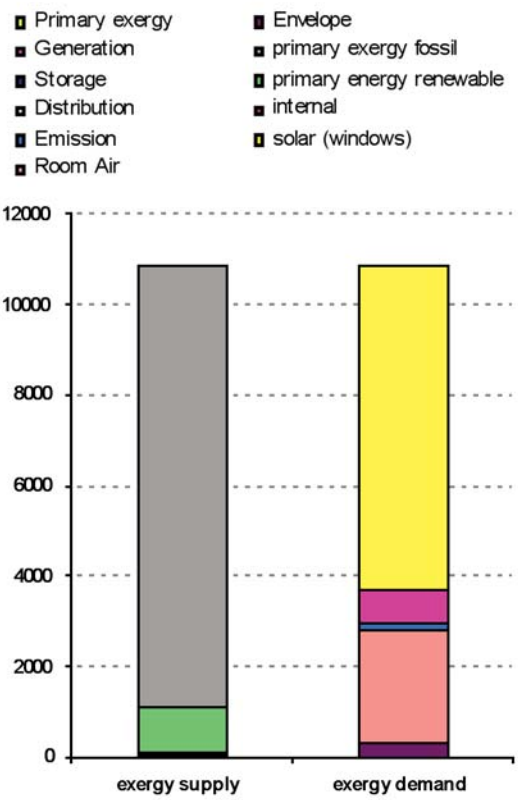


Figure 3.5: Exergy supply and demand.

Cascadia represents the building as a simple thermal load and emphasises more in the form of the energy supply and its distribution network. It adapts the model to represent the neighbourhood design as illustrated below.

Keeping in mind the concerns relating to urban design and energy use and in particular the desire to reduce the need for fossil fuels, the model can be used to examine the implications of different energy supply technologies, urban formats and heating techniques in terms of their overall energy and exergy usage. The evaluation was intended to answer questions such as:

- Is thermal efficiency the same as exergetic efficiency?
- Does the use of renewable energy impact the exergetic efficiency?
- Is it practical to cascade the heating needs of buildings?
- What would the building mix look like to support a district energy system?
- Is the use of exergy as an indicator, visibly different in terms of performance?

3.3.2 Model Assumptions

The model of the neighbourhood consists of a centralized energy plant supplying a district heating piping network. The district energy concept is utilised to take advantage of a variety of energy supplies. Heating loads consist of a typical neighbourhood and include high-rise apartment buildings, low-rise or detached residential homes and a retail sector comprising strip malls or single storey retail buildings. Individual buildings are connected to the district energy system in a parallel configuration with the supply and return lines. The three categories of buildings – high rise, residential & retail, are connected sequentially.

The model includes an allowance for both space heating and internal electrical loads. Building details provided to the model relate to the heat loss and ventilation requirements of the building and the electrical loads (pumps, fans, plug loads, etc) associated with the building and distribution system.

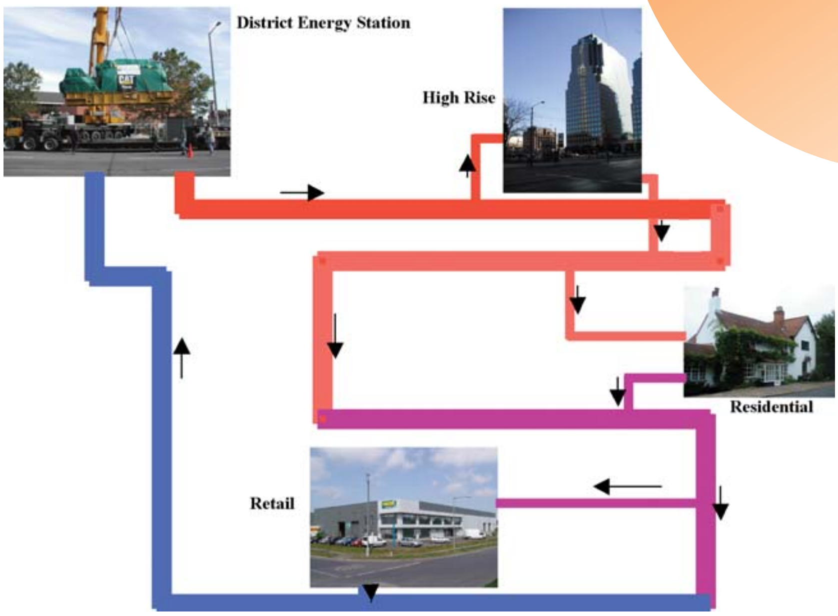


Figure 3.6: Neighbourhood model implemented in the community MS Excel calculation tool Cascadia.

Table 3.3: Example Building Design Data.

		High rise		Residential		Retail / Commercial	
Building FloorPlate Area		303	square metres	99	square metres	14000	square metres
Numberfloorsperbuilding		5		2		1	
FloorHeight		3	m	3	m	6	m
Numberofbuildings		20		75		12	
Volume		90900	cubicmetre	44550	cubicmetre	1008000	cubicmetre
Floorplates		30300	square metres	14850	square metres	168000	square metres
losses		2300	watts/deg C	1400	watts/deg C	3000	watts/deg C
indoortemperature		20	C	20	C	20	C
Design Temperature		-29	C	-29	C	-29	C
Transmission Losses		2254000	watts	5145000	watts	1764000	watts
airexchange		3	perhour	1.5	perhour	1	perhour
		0.000833333	persecond	0.000416667	persecond	0.000277778	persecond
heatexchangerefficiency		85%		75%		75%	
Ventilation Losses		186515.4375	watts	76175.85938	watts	1149050	watts
Gains							
Numberoccupants		1200		125		250	
wattsperoccupants		80	watts	65	watts	25	watts
Thermal gain - occupants		96000	watts	8125	watts	6250	watts
specificinternalgainsofequipment		1.36	wattspersquare metre	1.36	wattspersquare metre	0.5	wattspersquare metre
internalgainsofequipment		41208	watts	20196	watts	84000	watts
TOTAL THERMAL GAIN		137208	**watts**	28321	**watts**	90250	**watts**
THERMAL DEMAND OF BUILDING		2303307.44	**watts**	5192854.86	**watts**	2822800.00	**watts**
Electric Power							
Lighting	specific	2	watts/square metre	2.2	watts/square metre	1.2	watts/square metre
	power	60600	watts	32670	watts	201600	watts
Ventilation	specific	0.5	wattshourpercubicmetre	0.3	wattshourpercubicmetre	1	wattshourpercubicmetre
	power	136350	watts	20047.5	watts	1008000	watts
Appliances	specific	1.2	wattspersquare metre	1.6	wattspersquare metre	0	wattspersquare metre
	power	36360	watts	23760	watts	0	watts
Plug Loads	specific	0.3	wattspersquare meter	0.4	wattspersquare meter	1.5	wattspersquare meter
	power	9090	watts	5940	watts	252000	watts
TOTAL		242400	**watts**	82417.5	**watts**	1461600	**watts**

The model includes an allowance for both space heating and internal electrical loads. Building details provided to the model relate to the heat loss and ventilation requirements of the building and the electrical loads (pumps, fans, plug loads, etc) associated with the building and distribution system.

Table 3.3 outlines the details required to model the building designs. These designs are considered only representative for the purposes of this analysis and only serve to provide nominal thermal and electrical loads. The number of buildings in each category enables the temperature drop in the district energy system to be determined by balancing the water flow rate required.
For the evaluation process the district energy supply temperature is selected, based upon the capabilities of the supply technology. Five technologies were included within the model:

1. a medium efficiency gas fired boiler,
2. a high efficiency, condensing gas fired boiler,
3. a reciprocating gas fired engine based cogeneration system,
4 an electrically driven ground source heat pump
5. flat plate solar thermal collectors.

For options 1 to 3, the initial exergy level is related to the combustion temperature of the fuel. Electrical power where not provided by the neighbourhood system (i.e. in options 1, 2, 4 & 5) is assumed to originate from a utility owned gas fired simple cycle cogeneration system.

In the district energy loop, the supply temperature is considered to be 90°C for the first three options and reduced to 54°C for the heat pump and solar panel options. Heat distribution within the buildings can be either forced air or radiators where the radiator design is to DIN 255 standards for the supply temperature to maximise their efficiency of operation. Efficiency data for the building components described in the Annex 49 pre-design tool were taken here as well.

3.3.3 Ambient Temperature

The reference temperature for exergy calculations can be chosen by the user.

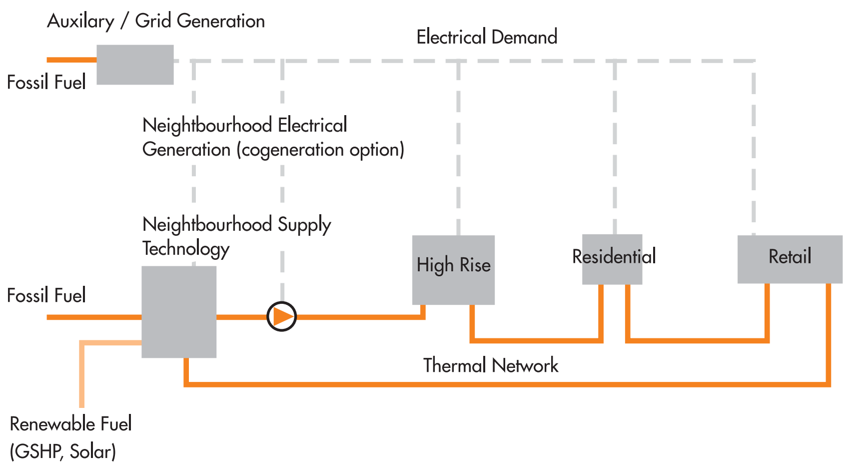
3.3.4 Output

The results of the analysis are presented in terms of:

1. energy efficiency of system – heating and electrical demands as a percentage of input primary energy – this illustrates the amount of energy usefully deployed as space heating or as available electricity
2. exergy efficiency of heating system – heating and electrical exergy demands as a percentage of available exergy – illustrates the exergy consumed in space heating and generation of available electricity.
3. exergy efficiency of overall system – the total exergy consumed in the process of space heating and power generation as a percentage of the overall exergy available – this illustrates the exergy lost on the delivery system.
4. fossil fuel efficiency – heating and electrical generation energy as a percentage of fossil fuel energy input – illustrates the potential for reduction in fossil fuel demand.

For reference, a baseline case was developed that describes a conventional district energy system fed by a gas fired, standard efficiency boiler. All buildings in this situation are connected in parallel and receive water at 90°C. They return it at 80°C with heat being distributed throughout the building using forced air circulation.

A series connection between the different buildings is also possible, so as to allow the district energy water to cascade thermally from the high rise to the residential and thence to the retail buildings.



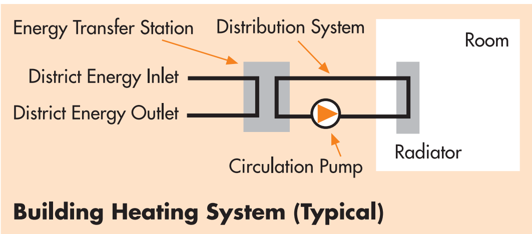


Figure 3.7: Illustration of the baseline case for the neighbourhood analysis.

3.3.5 Example of analysis: a case study

3.3.5.1 Baseline case

The baseline case mentioned above is used as basis for comparison. This system is typical of (at least) Canadian district energy system where minimal alterations or commissioning if effected on the distribution network within the customer building.

In this option, the effective use of the heating energy is poor. While the system energy efficiency is calculated to be 57%, the low exergy efficiency (3.8%) suggests that a great deal of the energy's potential use is wasted.

3.3.5.2 Cascaded Option

The district energy piping network is reconfigured to link the various categories of buildings in series. The district heating system therefore provides 90°C water to the high-rise buildings, followed by the residential buildings and finally the retail sector. To maximise the distribution of the heat within the various buildings, hydronic radiators would be employed in the high rise and the residential buildings. As in Europe, the hydronic systems would be designed to DIN standards appropriate for the temperature ranges associated with the building category. A forced air distribution system was retained within the retail buildings.

Since neither the ground source heat pumps nor the flat plate solar panels could provide 90°C, the supply temperature to the high rise buildings was reduced to 54°C. Again, the distribution in the high rise and the residential sectors was assumed to be hydronic with forced air in the retail sector.

When examining the results, the use of a standard boiler increased the overall system efficiency from the baseline value of 57% to 58.3% and this was largely due to lower pumping energy required for the use of the hydronic system in the high rise and the residential buildings. While not common in North America they are undoubtedly more efficient than a forced-air system, especially when the final elements, the radiators, are correctly sized.

Cascading of the energy loads within a district energy system does provide some improvement in exergy use. The exergy efficiency of the standard boiler district energy system was seen to increase from 3% to 7.4%. For a high efficiency boiler system it reached 9.5% implying greater use of the available resource but still leaving significant room for improvement. At this low level of overall exergy use it can be seen that the exergy used within the distribution system (pumps, fans, etc) is almost as large as that consumed in the heating of the buildings themselves. This highlights the need for the designer to select high efficiency pumps and fans.

Table 3.4: Baseline case.

	Primary Energy (MW)	Energy Efficiency (%)	Useful Exergy Efficiency (%)[17]	Total Exergy Efficiency (%)[18]	Fossil fuel Efficiency (%)[19]
Standard Boiler	20.4	57	3	3.8	57

Table 3.5: Cascaded option.

	Primary Energy (MW)	Energy Efficiency (%)	Useful Exergy Efficiency (%)	Total Exergy Efficiency (%)	Fossil fuel Efficiency (%)	District Energy Return Temperature (C)
Standard Boiler	20.4	58.3	7.4	13	58.3	40
Condensing Boiler	15.1	74.7	9.5	17	74.7	40
Cogeneration	44.7	66.9	41	47	66.9	40
Ground Source Heat Pump	11.5	40.9	5	9	61	36
Solar Panels	13.3	77	40	71	335	36

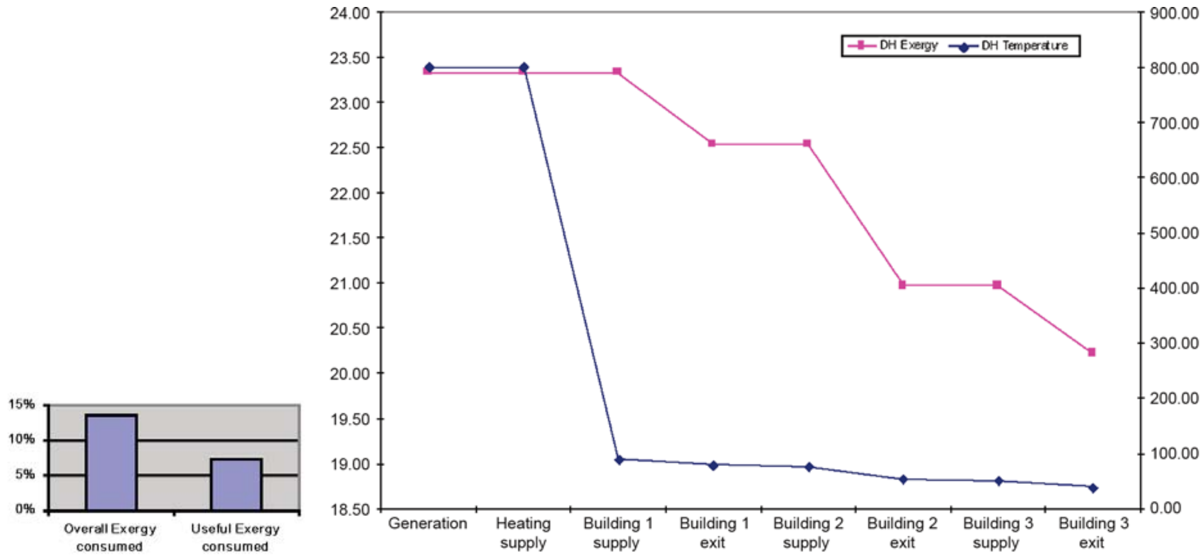


Figure 3.8: Standard Boiler.[20]

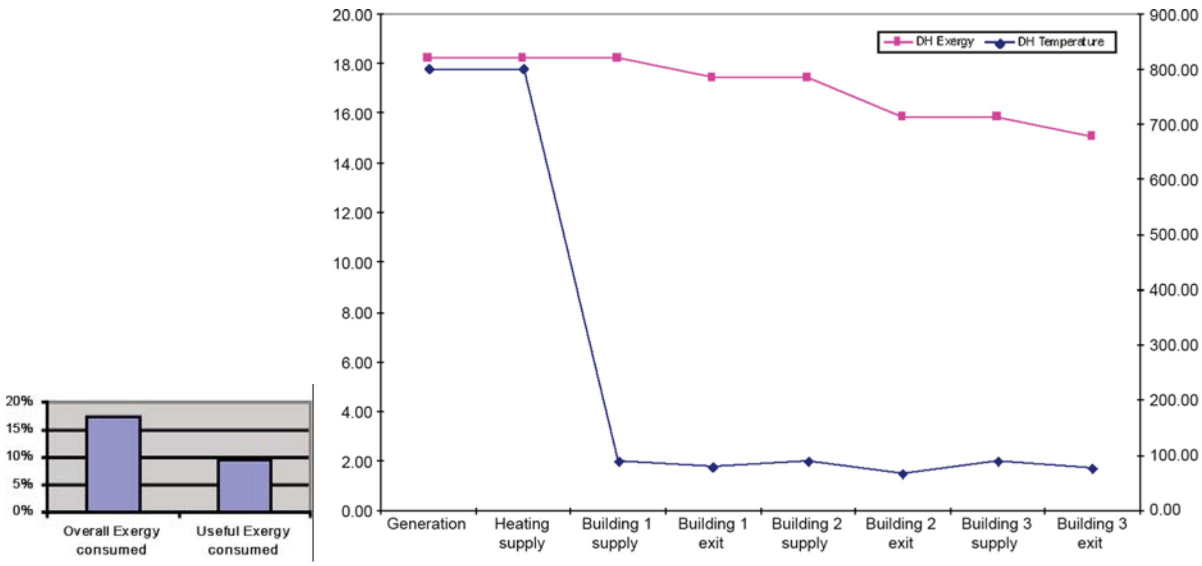


Figure 3.9: Condensing boiler.

The introduction of cogeneration as both the thermal energy and electrical energy generator created the most significant increase in the use of exergy. In the analysis the cogeneration system was sized for the thermal load of the buildings. This counter to the conventional design of in-house cogeneration systems and would produce more electricity than is needed within the buildings. As such the design would require the availability of an electrical grid or some other mechanism to utilise the excess generation. The approach would also consume additional gas to produce electricity, more than was required for the building loads. Overall, from an energy perspective, the system was less efficient than a condensing boiler. However, from an exergy perspective there was a significant improvement over the boiler driven systems. This increase in exergy efficiency is attributable to the generation of valuable electricity (i.e. with high exergy content) from the cogeneration system.

The use of ground source heat pump as a heating technology is praised by many as a good use of renewable energy. As is seen though, while the need for fossil fuel heating is significantly reduced (demand has reduced from 20.4 MW to 11.5 MW) the efficiency of its use does not improve.

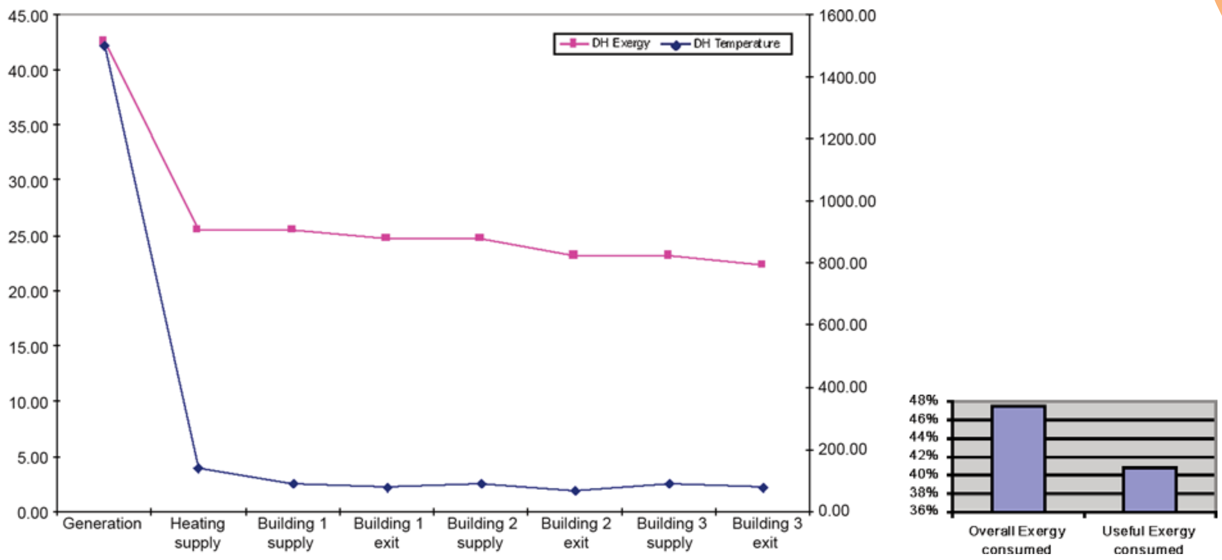


Figure 3.10: Cogeneration.

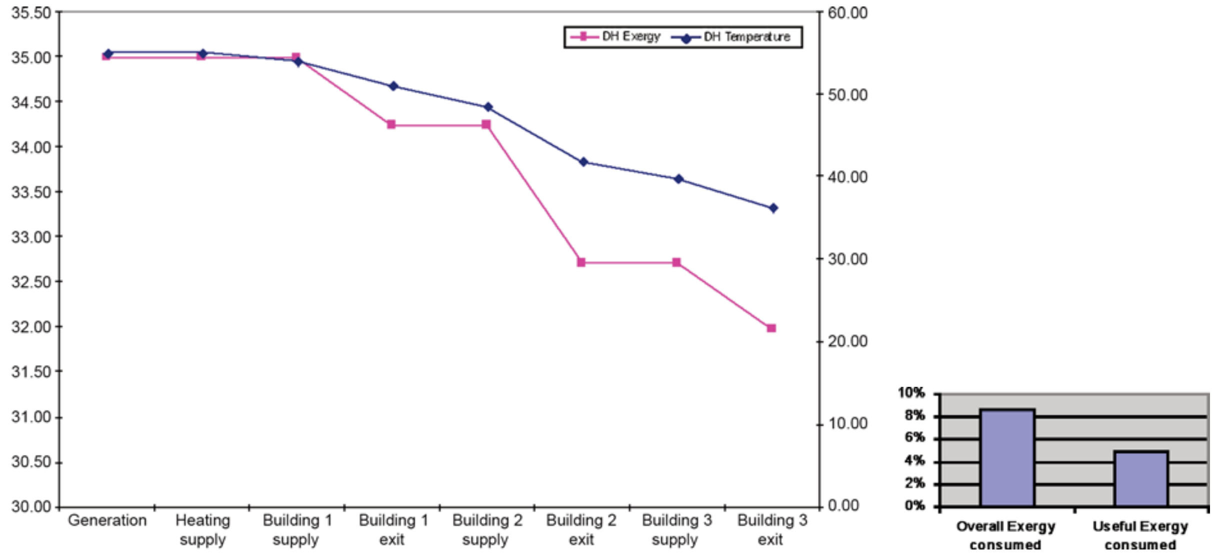
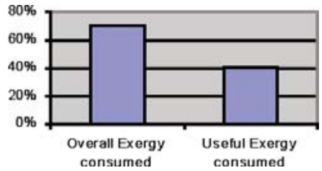


Figure 3.11: Ground source heat pump.

Despite the reduction in fossil demand, the exergy efficiency of the overall system is significantly reduced due largely to the need for exergy expensive electricity for the compressor. This demand is, of course, interrelated to the ground water temperature and the supply temperature to the buildings; the greater the temperature lift, the lower the pump's Coefficient of Performance (COP) and the greater the demand for electricity.

The use of solar thermal collectors appears to offer the most significant all-around improvement. In contrast to the ground source heat pump, no additional electrical load is required to operate the collectors, minimising the electrical needs to the circulating pumps and the in-house building loads. The lower supply temperature increases the overall exergy efficiency and the heating value as a fraction of primary (fossil) fuel requirements is very high. It should be noted that for the solar option, the use of seasonal storage was included in the calculations although it should be considered in further evaluation.



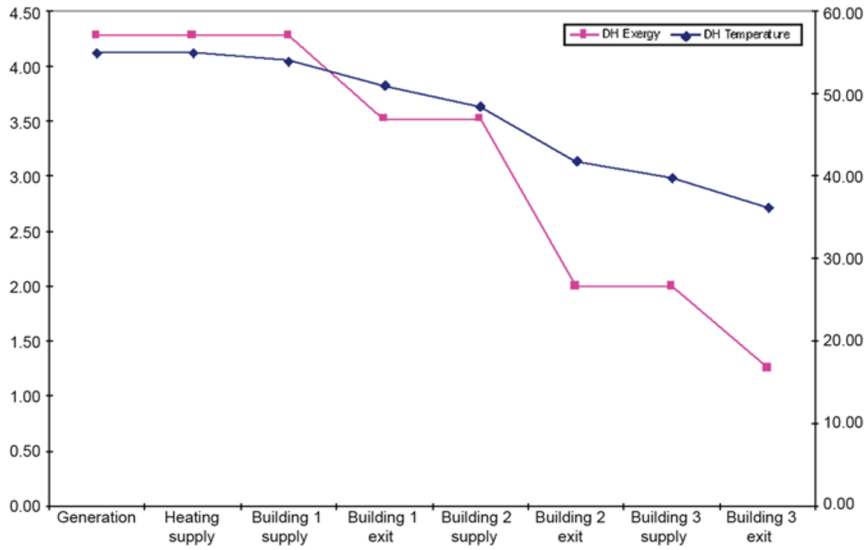


Figure 3.12: Flat plate solar collectors.

3.3.5.3 Conclusions

From this basic evaluation, there are several suggestions that could be made as to changes to the design and operation of neighbourhoods that would improve the use of energy and its exergy. These modifications range from the supply side to the final end-user demand.

Within the buildings, a move away from forced air distribution to hydronic will be a significant change for many building designers and contractors. However, the efficiency gain and reduction in high exergy demand (electricity) will be noticeable if supplemented by a switch from a standard to a condensing boiler[20] or to a cogeneration system.

At the neighbourhood level, distributing the heating through a district energy network is considered the only way to increase exergy use over and above the incremental improvements due to technology. Connecting the buildings categories in series maximises this improvement.

In this way significant benefits accrue to the community, the utility and the developer, namely:

- Cascading of the energy stream can essentially triple the revenue for the district energy operator for the same primary energy input.

- Assigning specific ranges of supply temperatures to building categories provides the opportunity for consistent HVAC design, avoiding custom design issues and establishes a market to justify the change.

- High-rise buildings would receive the highest supply temperature and therefore the greatest degree of flexibility in the design of their internal distribution system. For example, the cost of pumping could be minimised.

- Residential buildings would receive the mid-range supply temperature. This would provide the HVAC with a market share that would be large enough to absorb the development costs for the modified distribution systems (fan-coil or radiator based). The medium temperature too, would offer the possible inclusion of other renewable supplies (e.g. solar, heat pumps, seasonal storage, etc).

- By providing low temperature heating to the retail sector, the building owners would have access to inexpensive heating for their circulation air. The spatial needs for the increased size of heat exchangers, etc would be most easily accommodated in the larger retail buildings.

- Connection of the building categories in a cascaded fashion would have minimal impact on district energy piping size and layout.

- The grouping of building categories would encourage the development of mixed neighbourhoods through the incorporation of adjacent high density, low density, and retail zones.

- There exists an opportunity to align energy prices according to energy grades: the higher the energy quality then the higher the price. Suppliers would actively seek opportunities to add lower grade energy users to the system.

3.4 SEPE (Software Exergy Performance Assessment)

SEPE is a MS Excel-based tool, with which it is possible to model and analyze the most common heating and cooling system components. It uses the iterative potential of MS Excel to perform steady state energy and exergy analyses. The fact that the software performs iterative loops and calculates the outputs on a physical basis increases the model reliability.

The various components of the heat production chain are modelled here as black boxes, each one with independent internal equations. By copying and pasting these equations and connecting the input and output variables for each component, it is possible to create a whole space heating and cooling system. Since the dependent variables are calculated by the single absolute temperatures, this ensures a quick connecting process and control over the operation itself.

To perform loops, once the required components have been placed and connected in the MS Excel sheet, the input variables (absolute temperature and pressure) need to be connected to the output ones of the loop. Once the iteration options have been enabled, the program automatically updates the values until convergence.

The ability to perform thorough and meaningful simulations relies on the user ability to model the system and adapt the existing components for his own needs. A heat exchanger is for instance used to allow heat exchange from the primary to the secondary loop but it is effective also as a heat recovery system in the air. In the same manner, a saturator can be used both for evaporative cooling and as a cooling tower.

So far, the following models have been developed and included in the software:

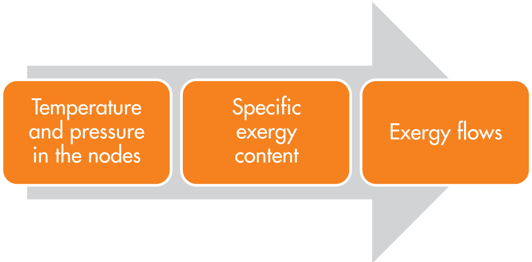


Figure 3.13: Exergy flows calculation steps.

The calculation of the exergy flows is performed by evaluating inlet and outlet pressures and temperatures in the nodes, given the reference temperature. By this, specific thermal and mechanical exergy are calculated in two different ways according to whether the medium is water or air. The computation of the exergy flows and exergy losses is then made possible by multiplying them for the mass flow passing through the system.

By means of this program wide possibilities of analysis and optimization are available. In the whole chain from generation to room system, through primary and secondary loops heat exchange, distribution and emission systems, exergy losses are found and therefore a better understanding of the weaknesses of the different systems is met.

3.4.1 Tool Layout

Every component with a single flow has the same shape and dimension to allow symmetry in the distribution of the components. It is divided into three areas:

- Left side: here all the inlet variables are given and calculated
- Central area: in this part all the internal parameters (such as the working fluid, mass flow etc.) are considered together with the defining equations
- Right side: here all the outlet parameters are yielded and displayed

Table 3.6: Available models in SEPE

GENERATION	EMISSION	DISTRIBUTION	OTHER MODELS
Boiler	Air handling unit	Air ducts	Room model
Heat pump	Floor cooling/heating	Water pipes	Heat exchanger
Chiller	Radiator	Fans	
Adiabatic saturator (for evaporative cooling)		Pumps	

INPUT PARAMETERS FIELD		USER-DEPENDENT AND SYSTEM-DEFINING PARAMETERS FIELD		OUTPUT PARAMETERS FIELD	
3		Boiler		Type:	Oil
	IN par	Env pressure	1	OUT par	
100000,0	Pressure	Env temp	273	Pressure	100000,0
0,0	Temperature [C]	Medium	Air	Temperature [C]	248,3
273,0	Temperature [K]	Mass flow [kg/s]	0,04	Temperature [K]	521,3
26132,7	Exergy [J/kg]	Heat flow [W]	10000	Exergy [J/kg]	98325,4
26132,7	Ex ph [J/kg]	Trise	248,3	Ex ph [J/kg]	100,0
0,0	Ex th [J/kg]	Primary energy	10526	Ex th [J/kg]	72192,7
		Eta thermal	0,95		
		Epsilon	0,9		
		Ex increase,flow [W]	2887,7		
		Ex loss [W]	6586	Eta ex	0,50

Figure 3.14: Example of a SEPE system component.

The system is naturally assembled from left to right, also improving the ease in reading. The only component allowing double flow is the heat exchanger. It is therefore composed by the superposition of two single sub-systems, as it is possible to connect a primary system (typically the generation one) with the secondary one (for instance, the distribution and the emission system).

3.4.2 Operation

The program is designed to be as simple as possible. It is easy to obtain a manageable layout by copying and pasting the subsystems from the components sheet and connecting them between each other. However, some principles should be followed in order to increase readability of the results. Although the placement of the subsystems doesn't affect the results, the hierarchical layout used is from left to right and upwards to downwards.

An innovative idea of the program is the way exergy is calculated. If no chemical transformations take place, than the specific exergy (i.e. exergy per unit mass) is a function of only pressure and temperature (Bejan, 1997). This means that by determining these properties in a node it is possible to calculate the exergy content. To do that, a heating or cooling system is split into sub-system components such as a boiler, heat exchangers, distribution devices like fans and ducts, emission systems and finally the room. Each sub-system has an input and output node. For each node pressure and temperature are known and therefore also specific exergy. By multiplying the specific exergy by the mass flowing in the node, the overall exergy content is known. By subtracting input and output exergy flows, the exergy destruction that actually takes place in the subsystem is easily determined. This destruction, which defines the process reversibility, is often the most problematic information to obtain. It is also the information required to determine the minimum entropy generation and exergy destruction, which SEPE can calculate easily.

The first step to model the system consists in the choice of a generation system, often connected to a heat exchanger. Figure 3.15 shows a possible system layout, where the dotted line represents the loop in a heat pump.

The systems are connected by linking the input variables of the N+1 system to the output variables of the system N. These variables are pressure [Pa], absolute temperature [K] and mass flow [kg/s]. For mass flow the connection is from N to N+1 compo-

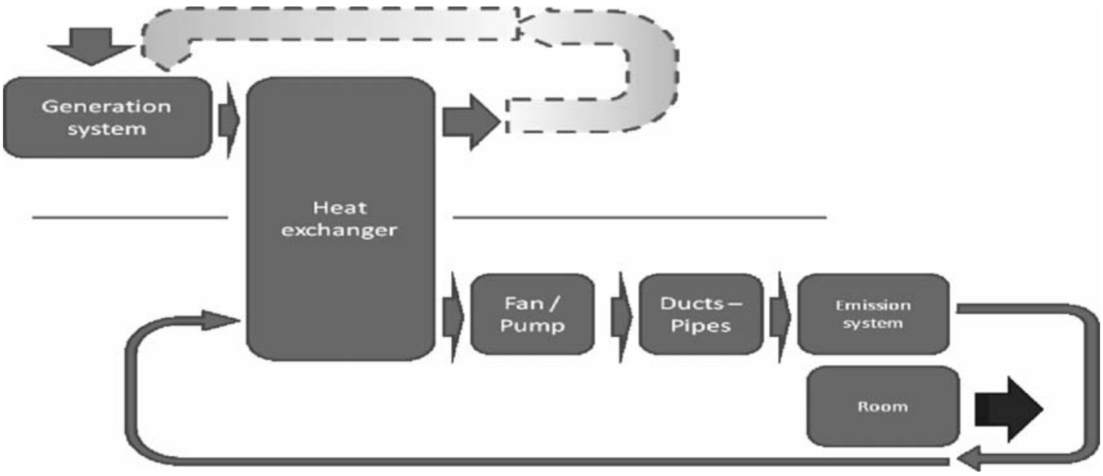


Figure 3.15: Example of a plant scheme.

nent in the primary loop, while in the secondary is from N+1 to N. This provides better control in the program, making it possible to quickly change the mass flow value in the generation system (primary) and in the emission system (secondary).

In Figure 3.16 a screenshot of a system with the components connections (arrows) is displayed. Starting from the left a boiler, a heat exchanger and a pump are displayed respectively.

As long as the system is placed, loops can be simulated by equating the outputs and inputs on the same level. In this way a waterborne system, for instance, can have outflow water circulating again in the heat exchanger.

The link between emission system and room system is different, as it needs more variables connected. Still, these are easily defined at the node connecting to room to the previous systems.

3.4.3 Generation Models

3.4.3.1 Boiler

A boiler system is a device that supplies energy to an energy carrier that in this case is air. Six different types can be chosen in the cascade tab in the upper-left cell, each with different efficiency and exergy fuel content. When chosen, an automatic update of the dependent values is done. The available fuels are: wooden pellets, natural gas, oil, chip wood and electricity. To each of the fuel is assigned a value for the thermal conversion efficiency and an exergy content.

3.4.3.2 Heat Pump / Chiller

Heat pumps and chillers are devices that transform electricity into heat by means of a reverse thermodynamic cycle. So far, to ease their use, they are modelled a black box. Their performance is usually greater than 3 units of heat per unit electricity as defined by their COP.

Figure 3.16: Components and connections in a waterborne system.

The control parameters are the mass flow and temperature lift from the heat source to the heat sink. The mass flow is the mass flowing in the system and the temperature lift is the temperature increase from the inlet to the outlet. The resulting heat flow is displayed in between.

Six different types of heat pumps are available and their selection can be made on the top left cell. Both waterborne and airborne systems are included, both with low and high temperature-lift options. According to this choice, the COP is set, which range from 2.5 for a air to air, high temperature-lift heat pump to 4.1 for a water-to-water low temperature-lift heat pump (Schmidt, 2004).

3.4.3.3 Solar collector

The solar collector model is derived from the heat exchanger. The upper half is used for solar radiation management while the downward one is dedicated to the heat vector. Two heat vector types are supported: water and air.

Radiation properties are controlled by a cascade list in the first row: possible selections are clear sky, turbid atmosphere and cloudy atmosphere. Solar energy radiation and quality factor are varied accordingly (1052, 415 and 447 W/m2 for radiation and 0.77, 0.51 and 0.507 for the quality factors) (Kabelac, 2005). The selection of the type of solar panel in the first row determines the energy efficiency of the collector, depending on the environment temperature, inlet temperature of the medium and sun radiation. The user is asked to insert the value for the collector area: the total radiation available at the solar collector surface is obtained by multiplying the surface area times the specific radiation.

Heat is then transmitted to the secondary branch of the solar collector: the heat vector can be selected in the grey cell in the centre: the properties of the heat vector, as well as the calculation of the specific exergy content are varied accordingly. Heat received by the heat vector is calculated by the total heat available times the efficiency of the solar collector, which also determines the outlet temperature of the medium itself.

3.4.3.4 District Heating

District heating makes heat for space heating available at different temperatures. There are three types available: high temperature (120°C), medium temperature (100°C) and medium-low heat (80°C) delivery temperature. The desired type, delivered heat temperature, Carnot factor and energy and exergy flows are automatically updated by changing the selection in the upper row. The user only has to give the mass flow as input, which will determine the heat and exergy delivered to the subsequent systems. Specific and total exergy content are displayed in the bottom of the right-side of the subsystem. The left side is not active as this model works as a heat reservoir.

3.4.3.5 Adiabatic saturator

The adiabatic saturator decreases the temperature of the air flowing in it by increasing the relative humidity until the wet bulb temperature is reached. The initial required value is relative humidity of the incoming air. Values are then processed in an external sheet and made available again in the output parameters area.

3.4.4 Distribution Models

3.4.4.1 Ducts / Pipes system

There are two sub-systems available to model the connections in the plants. There is an air duct for airborne systems and a pipe for waterborne systems. They are used for accounting for both the thermal and pressure losses in the connection systems.

The program automatically calculates the density and the kinematic viscosity, which are temperature dependent, thus yielding the Reynolds number. The main variables for the pressure losses calculation are clearly displayed on the coloured top bar to allow checking intermediate results easily. Pipes and ducts are considered circular, and the concentrated losses, due to bends for instance, are calculated as percentages on the distributed losses. The user-dependent sizing parameters are the pipe length, the diameter and the central insulation thickness ("Ins thickness").

With regards to the thermal losses, they are calculated assuming heat conduction through a cylindrical surface between the inlet and environment temperatures, with a thermal resistance calculated according to the user-provided insulation thickness and with an insulation thermal conductivity of 0.035 W/m²K. Total heat and pressure losses are then summarized in the central area. Exergy loss rate, accounting for both the thermal and pressure loss, is calculated as total specific exergy loss times the mass flow in the system.

3.4.4.2 Fan / Water pump systems

For fluid circulation devices, the options are a fan system and a water pump system. They compensate the pressure losses in the other components, and therefore the pressure rise ("Prise") must be provided to sum all the pressure losses in the other components belonging to the loop under investigation. The exergy loss figure is computed by subtracting exergy received by the energy vector due to the pressure increase from the available exergy given (electric power), input by the user.

3.4.5 Emission Models

3.4.5.1 AHU for heating and cooling

Two airborne emission models are available: AHU for heating and AHU for cooling. They are basically the same model, but two different equations for determining the room temperature are present to prevent numerical instabilities. If for instance during the iteration process the room temperature drops under the environment temperature in heating conditions, something physically impossible, no further meaningful solution can be reached.

The user provides an air mass flow and this value is picked up by all the previous systems in the secondary loop so that any change in the mass flow variable, which is a driving one, is automatically updated in the other systems of the loop. Heat exergy and energy flows are displayed in the lower part of the system. Particular care has to be taken in the coupling with the room model. In fact, this is the only case where a connection between two systems (emission and room) is not linear, as a loop has to be established.

3.4.5.2 Floor heating cooling and radiators

Waterborne models slightly differ from the airborne ones for their coupling with the room model. In the airborne system air is conveyed directly to the room, where it is assumed that it mixes with the environment. As a result the outlet temperature in the AHU model is the same as the room one and one fewer variable has to be calculated. Contrarily in waterborne systems outlet water temperature and room temperature are unknown. A calculation based on logarithmic mean temperature difference proved to be unstable. An approach based on heat exchange efficiency has been used instead. The determination flowchart is similar to the previous AHU model, but the emission efficiency accounts for the outlet temperature, which in principle differs from the room one.

The calculation of exergy flows and exergy loss also take into account the different physical processes involved in the heat emission process, while in the case of air there is heat and mass exchange, by delivery of exergy "quanta". In waterborne heating and cooling systems the heat exchange takes place without mass exchange in the building air. Room air temperature and inlet and outlet water temperatures are calculated by an energy balance between the heat loss from the room to the environment and the heat released from the waterborne system to the room. The exergy consumption that actually takes place in the exchange process is the difference between the inlet and the outlet exergy content of the water flow.

Pressure losses are so far assessed by means of a maximum nominal flow, given by the user in the top left cell. A pressure drop value at maximum flow is also declared in the centre area. The system linearly interpolates the pressure loss for mass flows different from the nominal one.

3.4.6 Environmental Models

3.4.6.1 Environment

The environment model gathers the information on the outside ambient conditions. Here the user defines the ambient conditions of pressure and absolute temperature (Celsius temperature is then derived). All other systems are usually connected to this subsystem to ensure that they are all working under the same reference conditions and to quickly propagate changes in the ambient conditions. However, as each subsystem features the environmental pressure and temperature, different choices are also possible. Where conditional formatting of the cells is available, this group assumes colours ranging from blue (for environment temperature below 15°C) to red (environment temperature >25°C), as well as through yellow-orange for intermediate ones. This clearly displays the working conditions of the HVAC.

3.4.6.2 Borehole

The borehole subsystem works like a sink or a reservoir of fluids in conditions that differ from the environment, for instance when a GSHP is connected. The borehole has a different temperature and can supply or absorb heat from the system.

3.4.7 Room Models

There are two types of room models: the first set is for Air Handling Units (AHU) and the second one for waterborne systems. The difference is due to the direct connection between the incoming air and the room air, thus making the coupling with the emission system simpler.

3.4.7.1 Room for AHU, heating and cooling

In the first column definition parameters for the system are present. The user is requested to insert U-values and area for walls and windows. Those parameters are needed to initialize a loop between Qloss, Troom and the inlet air temperature (picked from the AHU). When a stable solution is obtained, values of the Qloss and room temperature are displayed.

3.4.7.2 Room for waterborne systems, heating and cooling

Room model for waterborne system is quite similar to the previous one, but the calculation of the room temperature is slightly more complex than the previous case, because heat exchange has to account for the inlet and outlet temperatures. Two variables, outlet temperature and room temperature are unknown. The direct use of the 1st law of thermodynamics and the logarithmic mean temperature can lead to some instability.

3.4.8 Heat Exchanger Model

The heat exchanger module allows the connection of two different loops by letting heat flow from primary (usually generation) to secondary loop; input variables are, as usual, inlet pressure and temperatures in the first and second loop (respectively up and down).

The user is asked to define the medium of the loop. Water and air can be chosen and three types of heat exchangers can be used: water-to-water (U-value = 1000W/m^{2}K), air-to-water (U-value = 30 W/m^{2}K) and air-to-air (U-value = 20Wm/m^{2}K). Heat exchange is calculated according to ε-Number of Transfer Units (NTU) method (Çengel, 2006), both for parallel-flow and for counter-flow. The choice of the type of flow is done on the left top cell, in a tab pane. The user is also requested to insert the value for the exchange area while the program calculates the NTU on the U-value and the C_{min} (minimum heat capacity of the fluids) depending on the chosen energy carrier and on the mass flows, dependent on the other sub-systems. The effectiveness ε is then calculated on the basis of the flow type and on the NTU. The program automatically evaluates the outlet temperatures for both the first and the second loop.

There are three performance parameters for heat exchange in the model. Due to technical and physical constraint, for instance the finite heat exchange surface, not all the heat theoretically available is transferred from the primary to the secondary fluid. The ratio of the actual heat transfer rate to the maximum possible rate is quantified by the effectiveness. The thermal efficiency is a parameter that accounts for the thermal loss of the heat exchanger towards the environment. A perfectly adiabatic heat exchanger would have no losses towards the ambient and its energy efficiency would be 1. Still, its effectiveness could be smaller than 1, because the actual heat exchange can be lower than the theoretical one. The last performance indicator is the exergetic efficiency. Here it is defined as the ratio between the exergy loss in the primary loop and the exergy increase in the secondary loop. In this case the exergy content in the flow leaving the system in the primary loop is not considered an exergy loss.

3.5 Design Performance Viewer

The Design Performance Viewer (DPV) is a tool that helps extending the availability of exergy analysis directly to the architect or building designer. One limitation to the MS Excel-based tools is that often architects are not interested in utilizing MS Excel or text/calculation-based tools during their design process. This is especially true for the preliminary design phases when decisions about basic form and function are made. Unfortunately without inputs from exergy analysis, these initial decisions may overlook the benefits of some important design considerations.

The tool is built on top of existing Building Information Modelling (BIM) software. This software allows the designer to work with a visual model in 2 or 3 dimensions, while incorporating more than just geometrical data into the design. This extra data is parameterized within each of the building components, such that each wall and window has a U-value that is stored along with the fundamental size and location. The DPV utilizes the data set for the building to perform an energy and an exergy analysis that instantaneously produces simple charts and diagrams that help the user understand the impact of various design implementations on the building performance, both in terms of energy and exergy.

3.5.1 Building Information Modelling

The Design Performance Viewer shows the energy and exergy performance of a building using the BIM system interface. This allows the various parts of the building design to be compartmentalised within the model itself. Thus, the designer sees the building form along with its function in one model.

Still, for most BIM systems the input is not automated and retrieving significant information from the model can be difficult. The DPV takes a step toward a more simplified and accessible tool for the analysis of building performance. Not only that, but the tool takes the procedures developed by the Annex 49 group to include an exergetic performance aspect that has never before been integrated into a BIM model.

This is the first time a building exergy calculation has been implemented in a BIM tool, and it does so with calculations based on Annex 49 pre-design tool. Currently the tool integrates with the Autodesk Revit software allowing planners, designers, and architects to obtain an easy-to-understand graphical display of the energetic and exergetic performance of their building. The tool can be implemented in all phases of design and most importantly, allows the user to observe potential impacts of changes during the earliest and most influential phases of the design process. This facilitates an awareness of energy and exergy performance throughout a project, instead of energy analysis just being an afterthought at the end of a project.

It is not easy to design a modern building, and as buildings have become more complex so have the tools used to design them. Nearly all buildings today rely on some form of Computer Aided Design (CAD) tool in their creation. The need for higher performance buildings has led to the development of energy simulation tools that show not just the construction of a building, but also its operation. But often these simulation systems require complicated inputs, making analysis of various constructions or multiple design possibilities very difficult. The development of object oriented CAD models has facilitated the growth of more accessible energy analysis systems. These Building Information Models (BIM) include both geometric data as well as other information about various components of the building such as wall thermal resistance and room orientations. The information stored in the BIM can be used directly to do calculations about the design such as shading and lighting as well as energy calculations.

3.5.2 Development

The DPV tool takes information by using an application programming interface (API) from a Revit building model and uses it to determine performance factors for a building and display them in a simple graphical interface. The first version of the DPV was created for use in a 1-week course at the ETH Zurich called LowEx+Arch, and was used for a studio on the renovation of a particular building. With one click the students could see the performance of the building based on the German energy code (EnEV) calculations with different performance aspects like wall losses or solar gains compared in a spider graph. A Sankey diagram is also automatically generated of the energy flows. Finally, there is also a flow chart of the relative exergy destruction as calculated in the Annex 49 pre-design tool (see section 3.2).

The second version of the DPV expanded the flexibility, allowing any building type from offices to housing. This was then applied to a series of projects in the full LowEx+Arch course. The energy calculations were also updated to the Swiss SIA standard methodology and the graphics were improved to facilitate comparisons. The inputs in the tool are similar to those for the Annex 49 pre-design tool with drop down boxes for various installation types and heating systems. The input screens of the tool along with the spider graph, Sankey diagram, and exergy flow chart are shown in the following below.

The tool has now been utilized in several week-long courses as well as twice in semester courses at the ETH. The exergy aspect of the tool illuminates the importance of the type of system chosen by the designer, especially with respect to the temperature of operation. The value of low temperature heating and high temperature cooling is demonstrated in the use of the DPV, and it helps teach these concepts to the students

The third iteration of the DPV is under final development. The interface has been completely revamped and dynamic calculations including weather data are being implemented. Also the exergy calculations will be re-evaluated better to show the direct impact of certain design decisions, not just in the system drop down boxes, but within the parametric model itself. This is where the real preliminary design decisions are made, and if exergy can play a role there, it would become even easier to reduce the building primary energy demand. This latest iteration of the DPV is to be piloted again in the LowEx+Arch class. The software development is now part of a spin-off company from the ETH Zurich called Keoto (www.keoto.org). It will continue to be expanded and future additions include fully dynamic analysis as well as expanded compatibility with different types of BIM models.

3.5.3 Operation

The DPV is installed into the Autodesk Revit software. It can then be installed from the menu inside the Revit software. The software opens in a small window that allows the model continue to be viewed as shown in Figure 3.17.

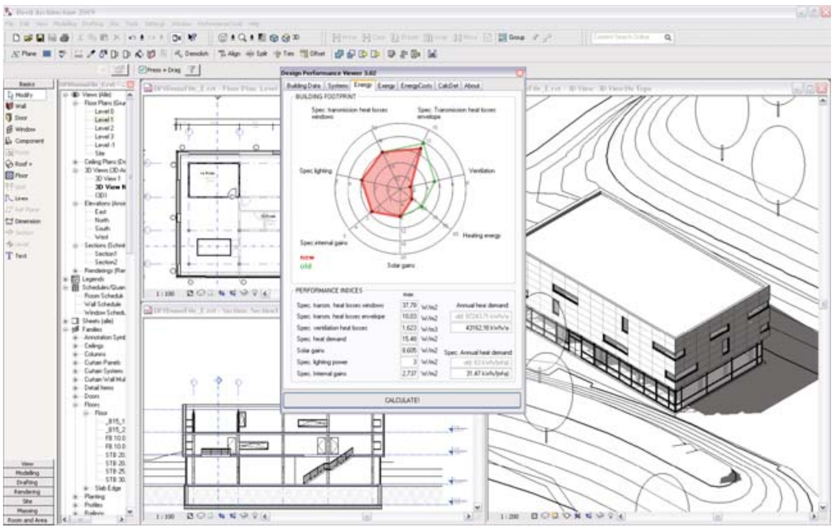


Figure 3.17: Screenshot from DPV software running on top of the Autodesk Revit BIM software.

Depending on the version of the software, there is a series of tabs that can be selected. The first tab on Building Data displays the information about the building itself. Unlike the Annex 49 pre-design tool, this information can be taken directly from the designer's BIM model. This provides the overview of the building geometry as shown in Figure 3.18.

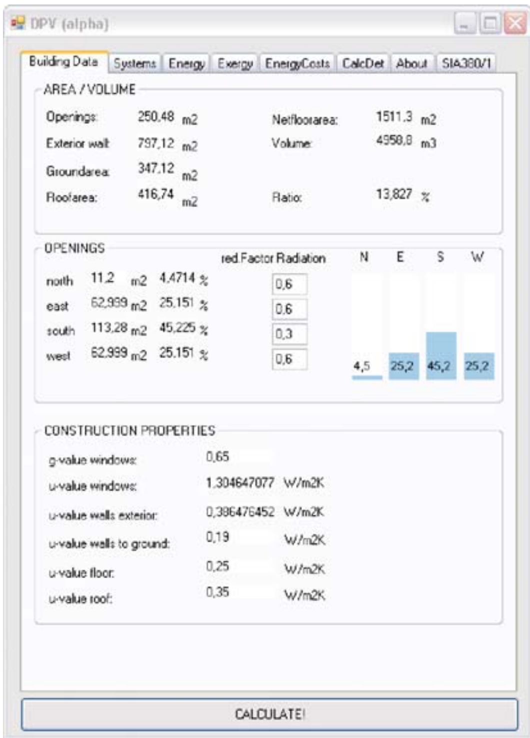


Figure 3.18: Building Data tab of the DPV software showing the calculations made for the building geometry taken from the BIM software.

In order to operate the tool, there are some inputs that must be supplied, which are similar to the inputs for the Heat Generation and Emission section of the Annex 49 pre-design tool (see 3.2). Because it is difficult to parameterize the building system components within the geometrically based BIM model, they must be entered here. These inputs are shown in Figure 3.19 in the Systems tab of the tool.

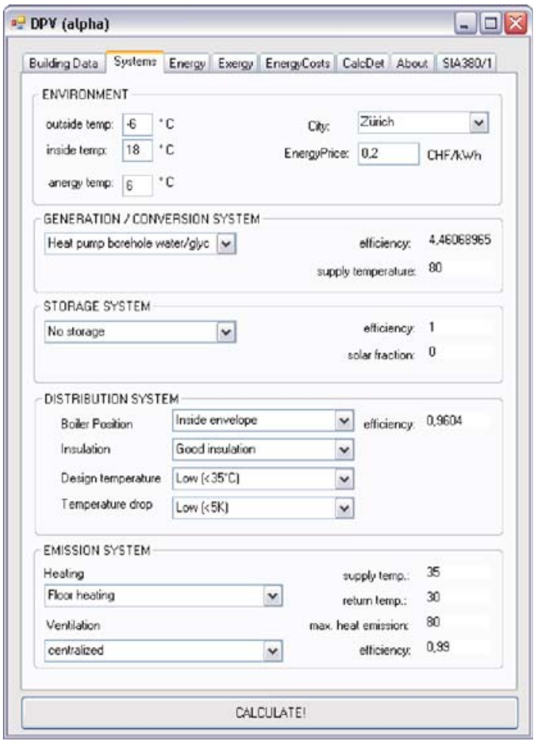


Figure 3.19: Systems input tab of the DPV Software.

At the bottom of the software there is a button that initiates the calculation, producing the results on the subsequent tabs. The calculation is done instantaneously and one can observe changes both made in the systems defined in the tool itself, as well as with changes made to the model in the BIM software.

This allows for an iterative design process where the steady-state performance of the building for a variety of potential design changes can be quickly calculated and observed. This is true not just for the energy analysis of the gains and losses in the building, but also for the exergy analysis, which demonstrates in which parts of the systems potentially valuable sources are lost or destroyed.

3.5.4 Output and Analysis

The subsequent tabs in the DPV provide the results of the energy and exergy analysis. The energy tab first shows a spider plot of the relative performance of the building in various factors. These are the transmissions losses of windows, that of walls, the space lighting, the ventilation, the internal gains, and the solar gains. As illustrated in Figure 3.20, the relative performance of these various sectors can quickly be observed and problem areas are obvious leading to rapid iterations of performance improvements. When new iterations are made the previous values are also retained for comparison as can be seen in the figure.

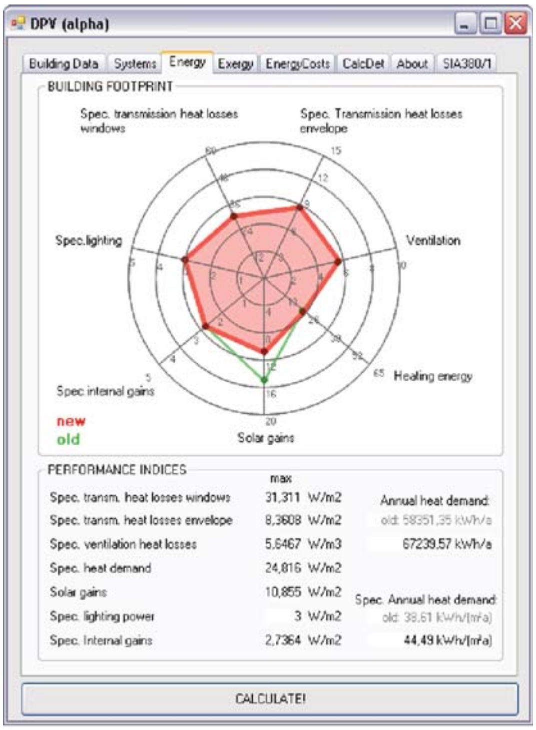


Figure 3.20: Energy results and spider graph of the DPV software for comparing the performance of different parts of a building design.

The Exergy tab includes both a Sankey diagram demonstrating the energy balance and flux into and out of the building as well as the chart showing the exergy flow through the building systems as shown in Figure 3.21. Again, the designer can view changes in the design or systems instantaneously, providing an understanding of the impact on energy and in this case also exergy use in the building.

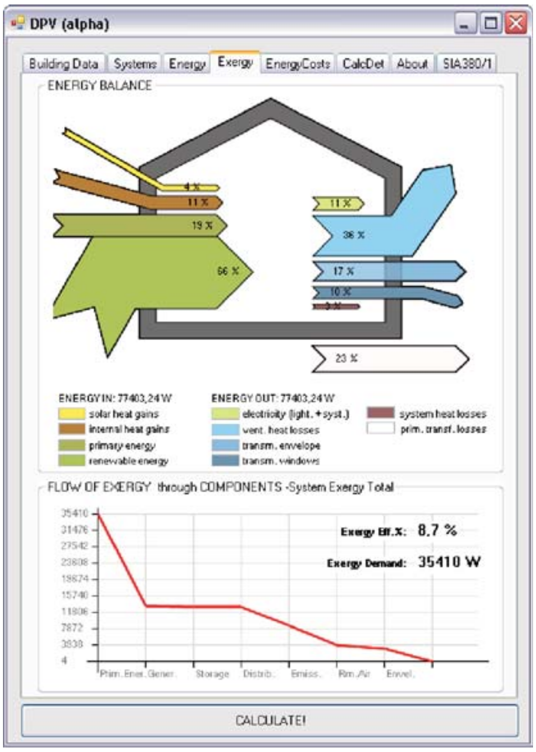


Figure 3.21: Exergy tab showing the energy balance and the exergy flow and efficiency in the DPV software.

3.5.5 Case Studies

The evolution of the DPV tool has taken place through a series of case studies and test implementations. The first versions were used in 1-week seminars at the ETH Zurich where students worked on optimizing various building designs using the tool. This helped to improve the outputs of the tool to better serve the users. Students worked on projects for the entire semester that used the DPV to optimize the system design for low exergy and high efficiency design.

The tool has also been used at the Summer Academy in Berlin with many international participants. It has also been a part of design courses at the technical universities in Bern and Lucerne in Switzerland. Finally, the tool has been exploited in collaboration with a large façade company, where the parameterization and energy analysis has allowed the company to further improve its products. The tool is being further improved to better serve industry in special applications such as this one.

3.5.6 Latest Version

The third (and latest (year 2010)) version of the tool incorporates some new calculations and has undergone a complete revamping of the source code. It also has a slightly new look and better interface shown in Figure 3.22.

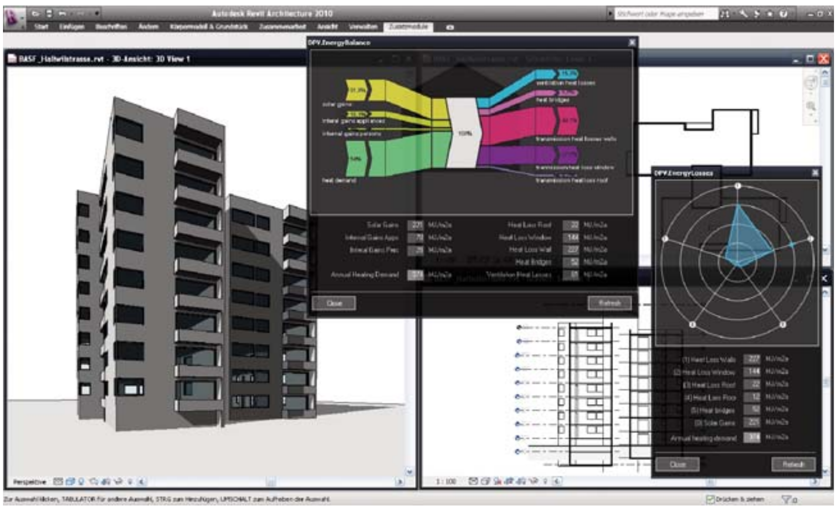


Figure 3.22: Latest version of the DPV Software.

3.6 Tool for calculating exergy of thermal comfort

In this section a MS-Excel based calculation tool for estimating the exergy associated with thermal comfort and energy processes within the human body is introduced.

3.6.1 Review on the application of exergy to thermal comfort

People spend a lot of time in the built environment. Their thermal environment has much influence on their quality of life. Therefore, it is important to investigate the built environment from the viewpoint of human-body exergy balance.

The development of human-body Exergy Balance theory started in the middle of 1990s by Saito and Shukuya. About 15 years before they started to develop the theory, Prof. Dr. I. Oshida, a Japanese scientist, who was one of the pioneering researchers in the field of solar exergy utilization, mentioned in his essay (Oshida, 1981), that there must be a relationship between the input exergy and output exergy of human body and thermal sensation, but he himself did not develop the theory of human-body exergy balance.

Saito and Shukuya developed the first version of human-body exergy balance model combining the energy balance and entropy balance equations for the human body using then state-of-the-art knowledge. They calculated human-body exergy balance under a thermally steady-state environmental condition assuming that the environmental temperature equals the ambient air temperature and mean radiant temperature. They found that the exergy-consumption rate within the human body becomes the smallest at the condition that metabolic heat-generation is equal to the outgoing heat. It suggests that the thermally neutral condition is provided with the lowest exergy consumption rate within human body (Saito and Shukuya, 2001).

The second version of human-body exergy calculation model was developed by Isawa, Komizo and Shukuya in the early 2000s. They made a few modifications of human-body exergy balance equation. One is to split the overall sensible thermal exergy transfer into radiant exergy and convective exergy. This enables us to calculate radiant exergy flux and convective exergy flux separately. The other is to improve the mathematical expression for sweat secretion and its evaporation; it makes possible the calculation for cases where indoor relative humidity is different from outdoor relative humidity. After these modifications, some theoretical re-examination on the derivation of liquid-water exergy and moist-air exergy was made more recently, since 2006, to reach its present version.

According to the human-body exergy balance calculation made for winter condition in the last ten years, there is a combination of mean radiant temperature and room air temperature providing the human body with the lowest exergy consumption rate; that is the mean radiant temperature from 23 to 26°C and the room air temperature from 17 to 19°C. Such indoor thermal environment is usually consistent with a good level of thermal comfort according to the experienced concerned architects and engineers (Isawa et al., 2002 and 2003). On the other hand, for summer conditions, it was found that a combination of mean radiant temperature ranging from 28 to 29°C and air current of exceeding 0.2m/s with a bit higher air temperature and humidity (30°C; 65%) provides the lowest exergy consumption rate. Such indoor thermal environment may well be provided with a high-temperature radiant cooling systems combined with natural ventilation and a good quality of solar control together with interior-heat-generation control (Shukuya et al., 2009). These results suggest that the development of the low-exergy heating and cooling systems is on the right track.

A recent study focusing on occupants' behavior and their thermal background in relation to human-body exergy balance (Schweiker and Shukuya, 2007) shows that the human-body exergy consumption rate of the occupant tend to become higher towards the time of closing windows and become lower afterwards, although this is based on the field measurement done in autumn season. They also investigated the difference of human-body exergy consumption rate in each occupant's thermal background (Tokunaga and Shukuya, 2009) conducted an experimental study on sweat secretion and its relation to human-body exergy balance in hot and humid condition. The subjects who are not much exposed to air-conditioned space at houses and other places could feel comfortable with a smaller rate of sweat secretion and a lower exergy-consumption rate within human body in comparison to those staying much in air-conditioned space.

3.6.2 Calculation tool

A MS-Excel based calculation tool has been developed. The original version of this calculation tool was developed as a FORTRAN code by Saito and Isawa. Figure 3.23 shows the appearance of the calculation tool. It consists of two parts: upper one to fill in the input values and lower to display the results of the calculation. A grey button in between is to execute the calculation. This calculation tool can output a human-body exergy balance at steady-state environmental conditions.

There are eight input values for calculating the human-body exergy: metabolic energy generation rate, clothing insulation level, mean radiant temperature, surrounding air temperature, relative humidity, air velocity, and outdoor air temperature and relative humidity. A detailed description of the calculation method can be found in chapter 2.3.1.

The tool consists of two subprograms: one is to calculate the temperature of the core, the skin and clothing surface based on a two-node energy balance model (Gagge et al., 1972); the other to calculate incoming and outgoing exergy fluxes together with the exergy-consumption rate within the human body. The calculation proceeds as follows:

1) Calculate the core temperature, the skin temperature, clothing-surface temperature and sweat secretion rate using the first six inputs values: metabolic energy generation rate, clothing insulation level, mean radiant temperature, surrounding air temperature, relative humidity, air velocity;

2) Calculate incoming and outgoing exergy using the three calculated temperature and sweat-secretion rate given by 1) , together with outdoor air temperature and humidity;

3) Calculate the exergy-consumption rate, the last unknown variable, substituting all of the incoming and the outgoing exergy fluxes obtained from 2) into the exergy-balance equation.

As you fill in the eight input values and push the button, "Execute Calculation", then you will find immediately the results of the calculation at the lower part of the calculation tool. The quantities displayed on the drawing of human body in Figure 3.23 are incoming and outgoing exergy fluxes and the exergy consumption rate. The unit of these quantities is Watt per one square meter of human-body surface W/m^2.

The three values appearing on upper right side of the human-body picture are calculated corresponding values of PMV*, skin-surface temperature and clothing-surface temperature. PMV* is a thermal comfort index which seems so far to take into rational consideration the effect of sweat evaporation for hot and humid conditions (Gagge et al., 1986).

In general, the exergy balance equation for a system is expressed as follows:

$$[\text{Exergy input}] - [\text{Exergy consumed}] = [\text{Exergy stored}] + [\text{Exergy output}] \quad (3.5)$$

The twin-bar graph on the bottom of Figure 3.23 indicates the whole exergy balance of human body. The upper bar shows all of exergy input rates and the lower bar the sum of the rates of exergy consumption, exergy stored and outgoing exergy. That is, upper bar indicates the first term of the left-hand side of equation (3.5) and the lower bar second term of the left-hand side, exergy-consumption rate, and two terms of the right-hand side of equation (3.5).

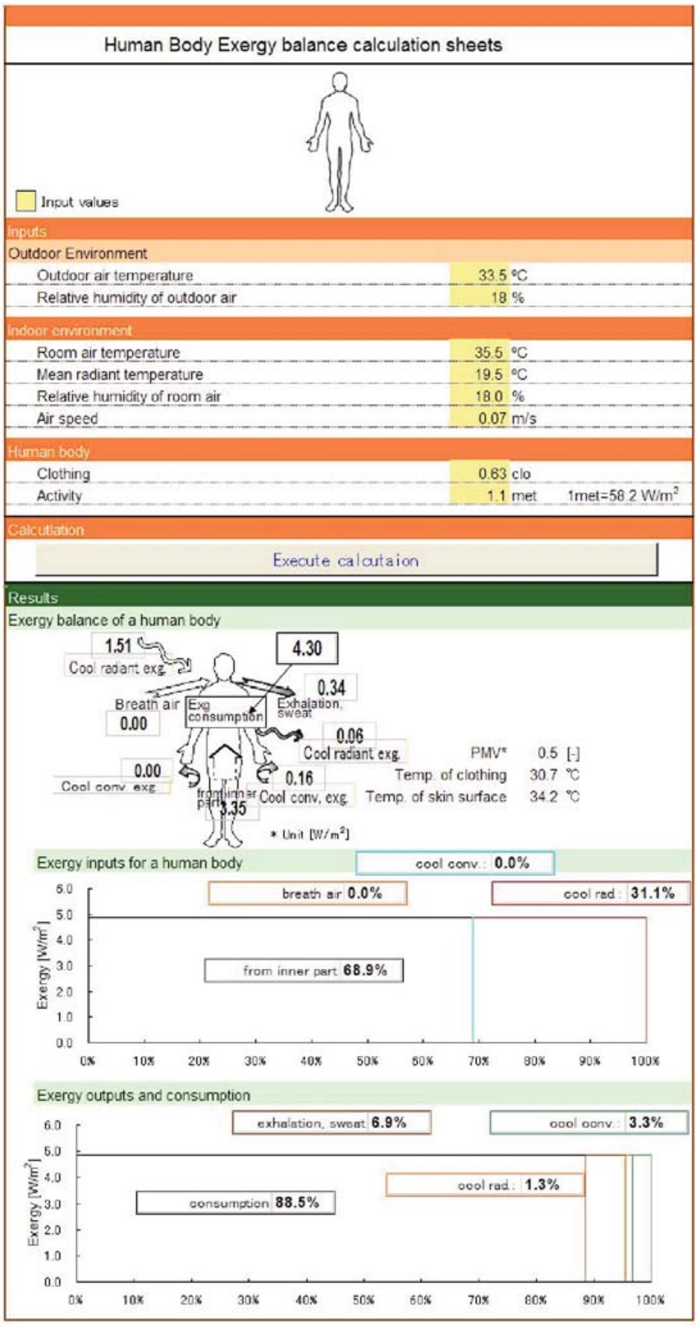


Figure 3.23: The Appearance of a Spreadsheet Tool for the Human-Body Exergy Balance Calculation

The height of the bars indicates the exergy rate. While on the other hand, the width of the bars indicates the percentage of the exergy rates of each component. The quantities on the bar graph are the percentages of each component.

This tool enables us to know the thermal exergetic aspect of human body in relation to a given indoor and outdoor environmental conditions.

3.7 Decision tool for energy efficient cooling for building retrofit[22]

The decision tree tool is intended to provide an overview on the different possibilities for energy efficient cooling when retrofitting a building. It shall serve as an instrument in the early phase of design in the discussion with HVAC designers.

Only systems available on the market in Switzerland at the time of the study are discussed. An important precondition is that the supply cooling water temperature to the rooms shall not be lower than 18°C, i.e. low exergy cooling emission systems are a prerequisite. The presented emission systems are all able to secure the required indoor climate with the high cooling temperature. Consequently, only generation systems which can produce a supply temperature of 18°C are considered. Due to this precondition mainly low exergy systems, such as natural heat sinks and chiller units with high COP, are considered.

The boundary conditions for the tool are set by the Swiss energy code SIA 382/1 (2007) which is based on EN 13779 (2007). Here the minimum requirements for glazing, shading, available building mass etc. which have to be fulfilled to be allowed to cool a building are defined. The design room temperature is not allowed to be lower than 26.5°C. A standard office environment with a cooling load of 30 W/m² was chosen as reference. The data gathered derives from system producers as well as from empirical values from Basler & Hofmann Consulting Engineers, Zürich. The decision tool is comprised of two main parts. The choice of emission system and the choice of generation system.

To find the appropriate emission system suitable for the existing building, the first step is to analyse the building design post retrofit and the desired range of indoor climate variation. This is done by means of a rose (Figure 3.24, to be read from inside and out):

	A (controlled relative humidity)							B (uncontrolled relative humidity)						
possible emission system	1	2	3	4	5	6	7	1	2	3	4	5	6	7
Metal cooling panels	X					X	X	X					X	X
Gipsum cooling ceiling	X					X	X	X					X	X
Gipsum cooling ceiling with capillary tubes		X	X						X	X				
Convective cooling panels	X					X	X	X					X	X
Free hanging cooling panels		X	X	X	X		X		X	X	X	X		
Fan coil	X	X	X	X	X	X	X							
Convection unit below window	X	X	X					X	X			X	X	
Cooling panel which activates the ceiling mass			X	X	X				X	X				

Figure 3.24: Table showing available systems in the Decision Tree tool.

• Is regulated indoor air humidity desired?
• What is the basic structure of the building?
• Which type of ceiling is intended?
• Are the ceilings constructed flat or with ribs?
• Does the building have window parapets?

By answering the questions, the number of potential systems is reduced. A table (Figure 3.24) shows which systems are available for the respective result-category A1-A7 and B1-B7. A comparison of the different systems is possible by comparing the system descriptions and the provided characteristics: efficiency, investment costs, annual energy costs and required surface area. The efficiency is defined as the emitted cooling energy relative to the electrical energy needed for the water circulation and, if applicable, unit fans.

The choice of generation system depends on the available heat sinks and whether waste heat of high temperature is available. Here descriptions of the different systems are given as well as characteristics. Of high importance is the efficiency, defined as the cooling energy produced divided by the electrical energy required. It defines a reference point as to how high efficiency should be expected.

The characteristics investment costs, annual energy costs and required surface area are given related to m² cooled floor area, resulting in a number which is easy for buildings owners and architects to recalculate to their specific case.

As every building is different, the calculated characteristics can not be generally applied. Especially the costs vary according to the specific situation, and the overall efficiency also depends among other things on the energy needed for distribution. The tool however shows the relation between the systems at the given boundary conditions.

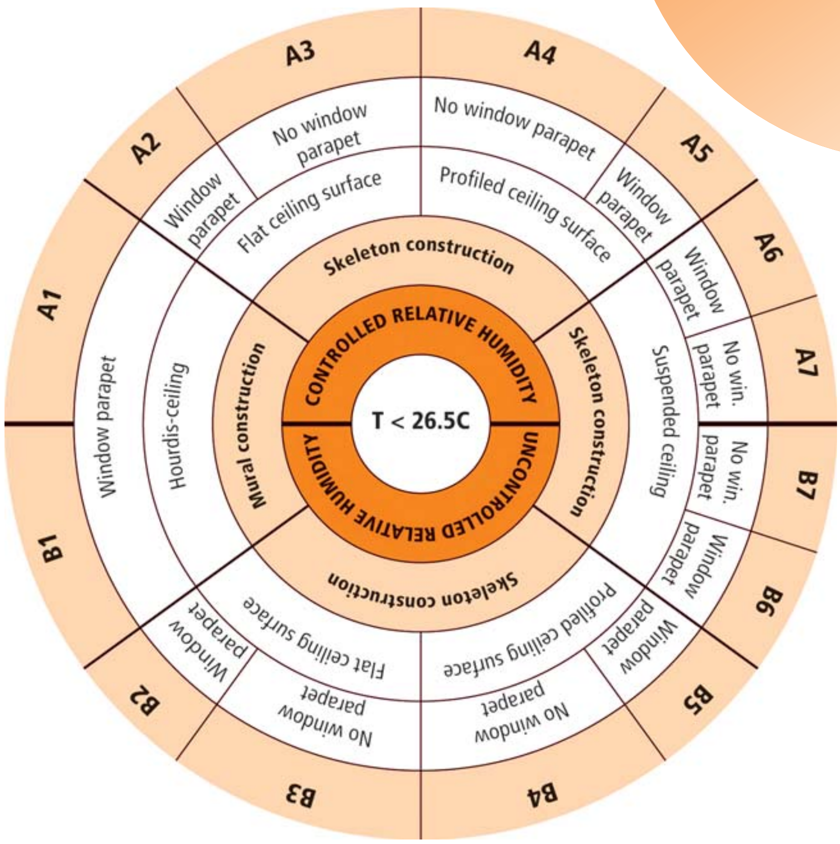


Figure 3.25: Rose for finding appropriate emission systems in the Decision Tree tool.

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[17]Fraction of exergy used in producing useful work / heat.

[18]Fraction of exergy consumed (i.e including exergy losses).

[19]Percentage thermal energy utilised per unit of fossil fuel consumed.

*[20]Remark: In the following figures showing the results (Figure 3.8 to Figure 3.12) the **overall exergy consumption** is defined as $(Ex_{in,\ primary} - Ex_{demand})/Ex_{in,\ primary}$; so it represents the percentage of the overall input which is being consumed on the supply process. However, it is very difficult to compare this parameter for different supply systems, since it does not give any idea on the total (absolute value) of the exergy losses. An increase in this parameter might be due to an increase in the exergy losses in the supply chain, but also due to a reduction of the total exergy supply, increasing the share of losses as percentage of the exergy supplied (this is what happens, e.g. in the cases of a standard and condensing boiler). **Useful exergy consumed** is defined as $(Ex_{demand})/(Ex_{in,\ primary})$; It represents, thereby the primary exergy efficiency of the investigated system.*

[21]It should be noted that the availability of Canadian condensing boilers of the capacity suited for neighbourhood energy utilities is limited but increasing.

[22]A more detailed description is avaiable at http://www.bfe.admin.ch/dokumentation/publikationen/index.html?lang=en

4. LOW EXERGY DESIGN STRATEGIES

To make exergy analysis reach a wider public of building planners and decision makers it is important to clearly state and summarize the central strategies that can be derived from this new approach. A wider use of the method will contribute to a significantly more rational and efficient use of fossil fuels, while promoting the integration of renewable energy sources in the built environment.

As stated in chapter 2, exergy analysis has already proved to be successful in optimising power plants and is making its way into building analysis (see the tools presented in chapter 3). The targets of exergy analysis applied to power plants and buildings are of course different in scope and aims. The optimisation of a power plant aims at increasing the output, i.e. the electricity produced. The reduction of the exergy losses in buildings aims, instead, at decreasing the exergy input to maintain the required outputs, i.e. the comfort conditions.

The core and first principle of the exergy method applied to the design of energy systems is to match the quality levels of the energy supplied and the energy demanded. In this sense, exergy can be understood as optimisation tool for the use of energy sources.

Applying the exergy method to energy systems in buildings contributes to increase their efficiency using both fossil and renewable energy sources, as it is shown for several building and community case studies in chapters 6 and 7.

An example showing the additional information offered by exergy analysis is the use of biomass or photovoltaic (PV) panels to provide space heating in buildings, as it is shown in the graphs in chapter 1. Although both are renewable energy systems and thus have a low environmental impact and CO_2 emissions allocated, the exergy quality of biomass and that of the electricity output from the PV panels is very high. Exergy analysis helps showing that these renewable energy sources should rather be used for equally high quality applications (e.g. lighting, mobility, etc.) instead of using them for low exergy demand heating purposes.

In this chapter strategies for a general design of energy supply systems in buildings and communities are introduced. Based on these strategies, implementation technologies presented both on a building and community level. Aspects related to control strategies and costs of the systems are also briefly discussed.

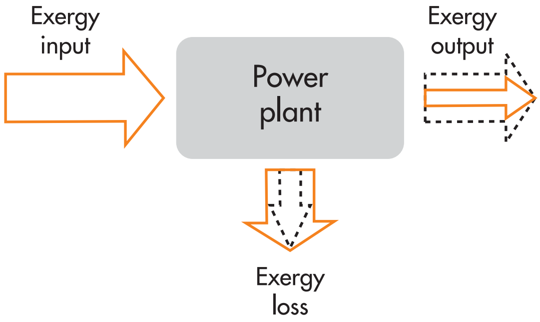

Figure 4.1: Power plant optimization aims at increasing the exergy output.

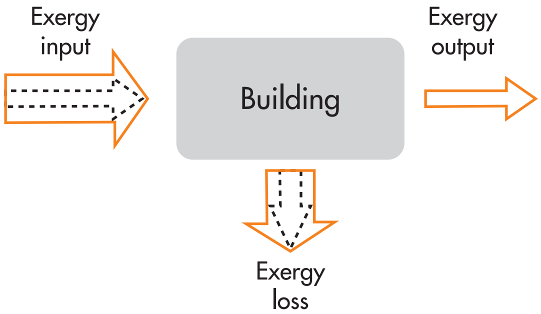

Figure 4.2: Building exergy optimization aims at decreasing the exergy input.

4.1 General design strategies for building systems

Buildings are major energy consumers (energy use for space and domestic hot water heating). Due to the low temperature level of most of these demands, their quality is very low (approximately a quality factor of 7%). The energy approach, in this context, intends to reduce energy demands in buildings by increasing insulation levels or increasing the air tightness of the building envelope, i.e. optimizing the building shell and later also an implementation of renewable energy sources. The exergy approach additionally requires the use of low quality sources for these equally low quality demands, i.e. by matching the quality levels of energy demand and supply (as shown in Figure 1.1).

Boilers are considered highly efficient energy supply systems. Their energy efficiency is close to 100%. However, their exergy efficiency can be as low as 5-10% because they degrade high exergy natural gas to rather low temperature heat. The core conclusion from exergy analysis on this basic level is that, in an exergy efficient energy system combustion processes should not be used for the production of low temperature heat.

Instead, low quality sources should be used for space heating and cooling applications in buildings. Examples of available low exergy sources are solar thermal heat, geothermal heat or process waste heat.

Additionally, low temperature heat flows existing within the built environment, such as heat in waste water or exhaust ventilation air, could also be used to supply a share of the energy demands via heat recovery systems. The use of these waste heat flows requires the use of innovative heat recovery concepts. Some examples of such systems are shown in chapter 6. These concepts already play a significant role in low energy building concepts. Taking into account exergy balancing, the mostly electrical auxiliary systems become more important. In order to minimize the high-exergy input in terms of electricity required for pumps and fans in these concepts, heat recovery connected to highly efficient energy systems, such as heat pumps is beneficial[23].

However most of the low exergy sources mentioned are not constantly available and almost important, are available in very limited power. Reducing energy demands in buildings consequently reduces the required peak power for space heating and cooling applications, making the use of low exergy sources more favorable.

In addition, lower specific power demands for space heating and cooling also allow the use of surface heating and cooling systems such as floor heating, chilled ceilings or thermally activated building components. Surface heating and cooling systems operate at lower temperature levels than conventional units (radiators or fan coils), thereby making also the use of low exergy sources more effective. Since these low temperature heating and high temperature cooling systems deliver the required heating or cooling energy at temperature levels closer to that of the energy demand in the building, they can be called low exergy emission systems. The use of these low exergy emission systems is a necessary step for a wider and more efficient integration of low exergy sources in building supply systems. In consequence, low exergy emission systems are "more flexible" since they allow the efficient integration of low exergy sources, but could also be supplied with high exergy sources. In turn, systems requiring higher supply and return temperatures such as old radiators with temperature levels of 90/70°C cannot be efficiently coupled with low exergy systems such as ground source heat pumps (GSHP) or solar thermal systems.

Yet, it is important to stress that the use of low-exergy emission systems is only a prerequisite for a low-exergy building, since low exergy needs with a high exergy supply would not improve the outcome from a standard building solution significantly.

For instance, a low-temperature floor heating system with a gas boiler would not perform much better than a high temperature radiator supplied by the same boiler (Figure 4.3).

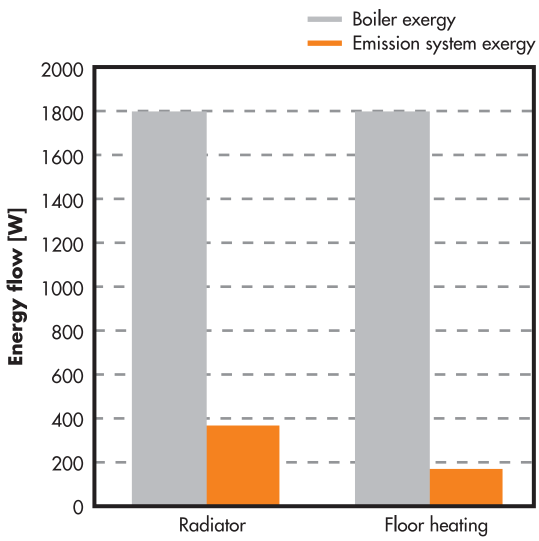

Figure 4.3: Comparison of exergy flow. The lower exergy need in the floor heating system gives no advantage since the boiler requires high exergy input regardless of the emission system.

The main focus to achieve an exergy efficient building supply is to decrease the quality of the source used and to find low exergy sources to be exploited for buildings.

As energy demands for space heating and cooling are reduced, the share of other uses within buildings such as domestic hot water (DHW) demands increases. The exergy quality factor of DHW energy demand is about 13%, being almost twice as high as for space heating applications. Energy systems using low energy sources show lower efficiencies for these demands on higher temperature levels. Strategies aiming at improving the performance of low exergy systems for DHW supply are desired and a promising future research topic.

In addition, higher and lower exergy demands within a building can be supplied one after another, following a cascading principle. This means that appliances needing higher exergy levels are served prior to appliances with lower exergy demand, making use of the same energy flow several times. Cascading of thermal energy flows in buildings is also a promising field which can be directly derived from the exergy approach and where future research is also required.

In addition to the concept and design of systems making use of appropriate energy sources for low exergy demands, control strategies of building systems to minimize exergy losses in the supply process are necessary. The first is step is the application of good building physics to reduce the energy demand of the building. Here a good insulation level, air tightness of the building envelope, the use of daylight and the passive use of solar energy are important factors.

4.2 Economic aspects in LowEx building design

Cost efficiency is a key issue in all building projects and in turn an important part of the development of low exergy solutions for buildings. Prototype solutions will always be more expensive compared to common market technologies. The potential of a new technology to perform better than a standard system the development of energy prices is a key factor. The cost efficiency of solutions is, in the long run, determined by the quality of the system design. High costs can therefore indicate that maybe better and more economic alternatives to reach the same result have been overlooked.

The development of components for low energy and low exergy buildings has been rather slow in the past. Solutions such as concrete core heating and cooling, waterborne solar collector systems and various heat pump solutions have been commercially successful on their own merits. There are solutions that have been commercially successful due to dual functionality such as floor heating where customers have probably been more often interested in the increased comfort rather than the exergy aspects. Waterborne radiative panels or chilled beams have often been chosen instead of air heating and cooling because of the comfort aspects, the reduction of fan electricity and operational costs being a positive side-effect. Offering a more comfortable system, integrating additional functions and advantages or positive side-effects (e.g. saved construction costs by reduced floor heights because of the integration of thermally activated floor slabs) is a key issue for the success of new systems. In recent years, efforts were made to integrate collector panels into façade or roof structures where the collector elements replace the normal cladding and, thereby, some costs can be saved. These technologies are still mostly in a prototype stage. There is also a known potential of saving energy by better control and a variable operation of the energy system in buildings, especially in commercial buildings. But, the costs of sensors and actuators and the wiring in residential buildings were still far too high to motivate private investment. With further development of the components and using wireless technology this could change if larger market potentials are identified.

4.3 General design strategies for communities

At the community level, generally speaking, two directions can be taken to address building related energy issues:

- the first focuses on the single building and aims at energy self-sufficiency (e.g. by designing zero energy buildings ZEBs)
- the other direction, characterized by higher complexity, aims at taking advantage of the variety of demand structures and available energy sources of a whole city by an integral energy supply and adjusted use profile

Very often, main efforts are directed to technological improvements for low-energy, self-sufficient and low-exergy buildings (e.g. by the development of so-called zero energy buildings (ZEBs), but this strategy can not have the same potentials as using synergies in communities instead of individual buildings. Communities are intrinsically characterized by a level of complexity and by a efficiency potential respectively higher than single buildings. At the community scale, however, it is possible to adopt deep-reaching changes in the supply structures, enabling the use of technologies that make a more rational and efficient energy use possible on a wider scale.

The core of the exergy approach for communities is similar to the building approach: the quality levels of the energy demanded and supplied shall match each other (see Figure 1.1). To accomplish this, the use of low exergy sources for supplying low exergy demands in buildings has to be promoted.

However, additionally to the similarities with the building level, communities supply strategies can offer synergies for an exergy optimized supply system design which can not be found in buildings, e.g. several demands with different quality levels are present, several low exergy sources can be linked to each other more efficiently and economically than in a decentralized supply, or a more efficient use of fossil fuels can be promoted more cost effectively and efficiently on the community scale.

The first step for a more exergy optimized community supply is, similar as for buildings, to promote a wider integration of low-temperature renewable energy sources, such as solar thermal or ground source heat. Higher solar fractions are generally achieved if solar collector fields are used in combination with heat networks, connecting several supply systems (e.g. collector or borehole fields) with different users. As the solar fraction increases, i.e. the share of low exergy supply increases, the exergy efficiency of the energy supply also rises. Similarly, the use of ground source based systems in combination with heat networks will increase the energy efficiency (i.e. COP) of heat pump units, if demands of higher temperatures, such as DHW supply, can be supplied by solar thermal heat. Solar thermal heat can be used in winter to reduce the required temperature lift from the heat pump units, allowing significant increase of the COP. This way high exergy input in terms of electricity required for operating the heat pumps can be reduced.

On the other hand, a more exergy efficient use of fossil fuels needs to be promoted. Decentralized supply with individual boilers should be substituted by electricity driven CHP units, maximizing the exergy output obtained from the high-quality fuels used. Distributed or centralised generation with CHP units can reduce the demand of fossil fuels and thus reduce the use of combustion processes for heat production in total, characterized by a high level of exergy losses.

As stated above, heat networks can play a significant role in a more exergy efficient energy supply on community level. They allow combining several renewable energy sources with waste heat from an exergy efficient use of fossil fuels. Heat networks also allow cascading energy flows according to their temperature, to supply high temperature applications, such as process heat, first followed by medium temperature demands such as DHW and finally low temperature heat can be directly used for space heating. In this way, pumping energy, i.e. high exergy input, into the network can be minimized and the exergy efficiency of the energy supply increases.

Exergy analysis can be a useful tool for improving the design of heat networks. Coming back to the two main strategies mentioned at the beginning of this section, and bearing in mind the main directions for promoting a more exergy efficient supply at the community scale, it can be concluded that designing more "sustainable" buildings could be regarded a necessary but not sufficient condition for reaching energy and exergy efficient communities. Innovative supply structures allowing the application of the strategies mentioned above are required.

From an exergy perspective pumping energy in pipes and ducts shall be minimized. This is also valid for the design of heat networks. For this purpose, the diameter of the pipes in the networks can be increased. Thereby, lower head losses can be found in the network and lower maximum fluid speeds occur. In turn, as a result of the greater pipe diameter, thermal losses in the network increase. First results on the sizing criteria of small scale district heating systems show that actually a trade off between the increase of (low exergy) thermal losses in the net-

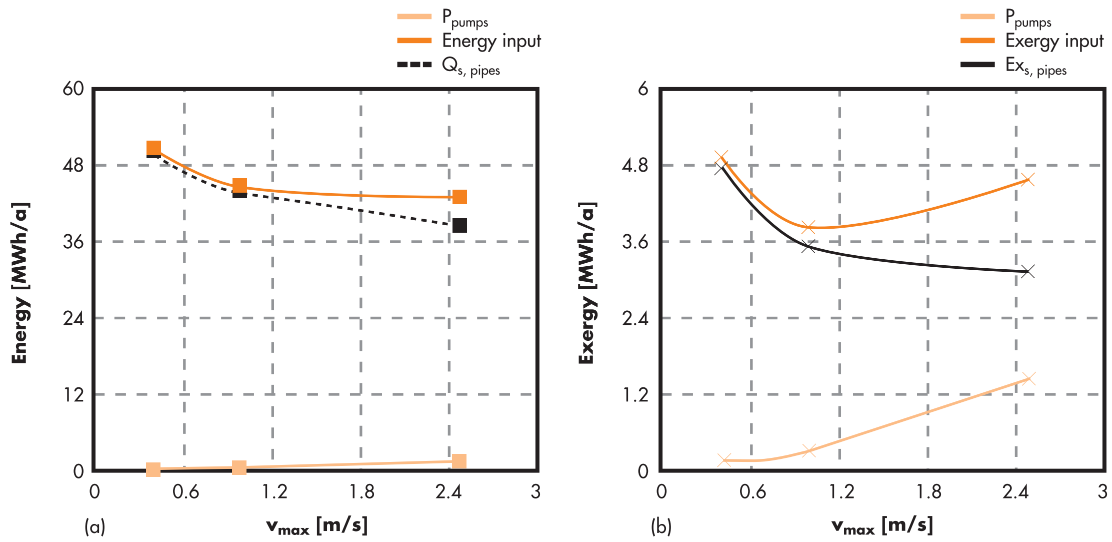

Figure 4.4: Pumping energy required for the operation of the heat network, thermal losses in the pipes and resulting required net energy input to supply both demands in energy (a) and exergy (b) terms (Torío, 2010).

work and the decrease in pumping energy for its operation can be found. While from the perspective of energy analysis lower target fluid velocities for sizing the network, i.e. smaller pipes, seem always advantageous, exergy analysis shows that an optimum between both criteria can be found (see Figure 4.4).

Storage units are also a key component in low exergy supply systems, particularly if based on heat networks to integrate a higher share of fluctuating renewable energy supplies (e.g. thermal solar power) into the system.

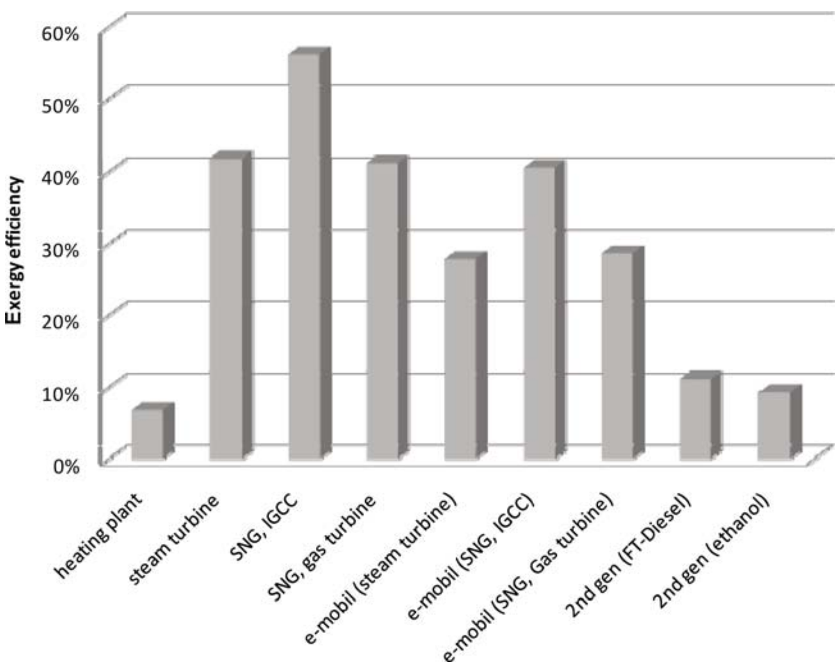

Figure 4.5: Exergy efficiency of selected woody biomass chains

4.4 Economic aspects in LowEx community systems design

Due to the different scale and the large number of decision makers involved, different technologies might be cost- efficient at the building and community level.

Considering technical-economic feasibility, solar photovoltaic and solar thermal systems, if properly integrated, can be well applied in the urban context. However, implemented community case studies show that the cost of these technologies as compared to their energy yield is still relatively high as compared to other systems such as district heating systems or heat pumps (Jank, 2009).

For this report the integration of biomass plants has been investigated in terms of economics and is outlined here as an example. The urban scale applicability of biomass is challenging because of plant feature problems, their location in the cities and management difficulties as well as supply and storage issues. On the basis of the actual conditions, biomass plants are more suitable in low-density urban environments and as close to the source as possible. Of course, in all cases with combustion (or pyrolysis or gasification) processes, CHP are recommended for improving both the energy and exergy performance. This is shown in Figures 4.5 and 4.6.

Figures 4.8 and 4.9 show the exergy efficiency of the different energy chains and uses for the woody biomass and biogas paths. It is clearly shown that biomass use for thermal uses has the lowest exergy efficiency of all investigated options. Thus, from an exergy perspective its use for these demands should be avoided. In turn, exergy efficiencies of biomass use electricity production and mobility are high. For a rational and efficient use of biomass resources, these technology paths and its use for supplying these demands shall be promoted (Kranzl, L. et al., 2010).

Figures 4.7 and 4.8 combine the exergy efficiency and the capital costs of several investigated systems for the biomass energy use chains. If we are separating the areas (1) thermal plants and CHP and (2) mobility (because the latter shows clearly additional costs for different reasons) we can observe that there is a clear trade-off between exergy output (efficiency) and capital costs (for the selected woody biomass chains this is an almost linear relation, for the selected biogas chains the situation is not that clear). This shows that there are higher investments necessary for a CHP compared to a thermal plant in order to make use of the full exergetic potential of biomass resources.

If we would follow the objective to gain a highest possible exergetic use of biomass resources with a minimum of capital cost, we would have to draw an envelope line in these figures connecting those points situated on the left hand and top side of Figures 4.7 and 4.8. This would lead to the conclusion, that using biomass for transport purposes in any case is not efficient, both from an exergetic and from an investment costs point of view. But, biogas plants feeding biogas into the gas grid and for combined heat and power production are an efficient option.

However, if we are considering that currently there is a high demand for individual transport systems, the lowest exergy losses result from bio-based e-mobility models compared to combustion engines. This would require clearly higher investment costs (which are partly offset, at least for the case of 2nd generation liquid biofuels by lower running costs).

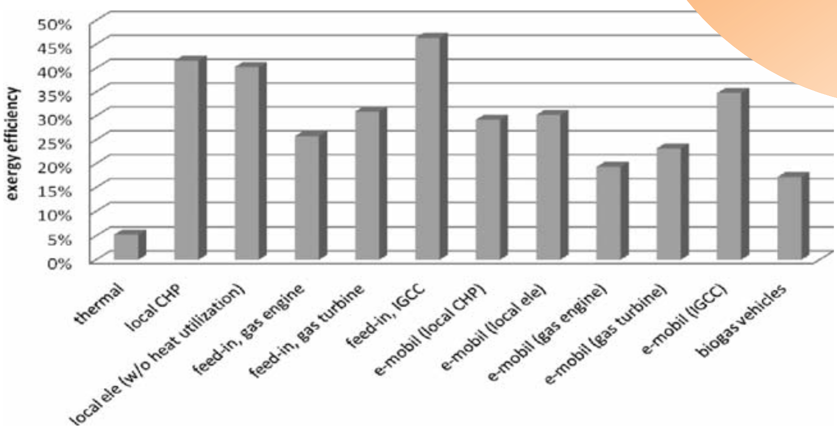

Figure 4.6: Exergy efficiency of selected biogas chains

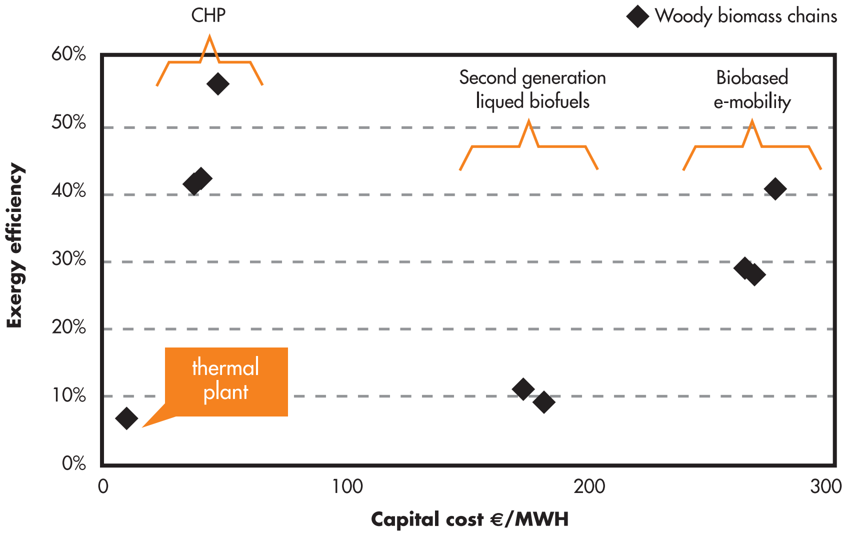

Figure 4.7. Exergy efficiency and capital costs (woody biomass)

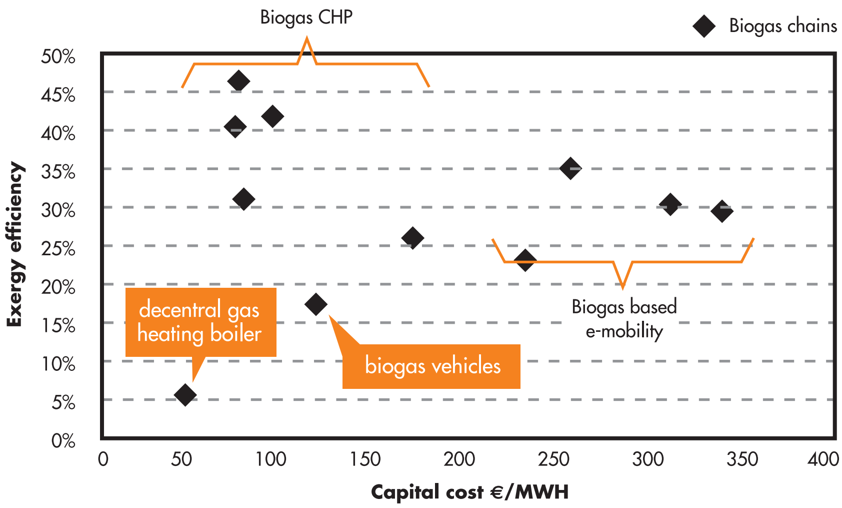

Figure 4.8: Exergy efficiency and capital costs (biogas)

[23] *In chapter 6 an example of such an innovative system is shown.*

5. EXERGY BENCHMARKING PARAMETERS

To complete the method for exergy analysis of building systems and bring it to the wider public parameters able to characterize the exergy performance of different systems are required.

A great number of parameters can be found in the literature (Cornelissen, 1997; Dincer and Rosen, 2007; Tsatsaronis, 1993). In this chapter the set of parameters considered as relevant by the Annex 49 group are presented. These parameters are used to characterise the performance of the building and community case studies found in chapters 6 and 7. The diagrams used for graphically showing the exergy performance of energy systems in buildings and communities based on the parameters introduced, are also presented. Additionally, a benchmarking proposal for characterising the performance of building systems is also introduced.

The main added value of the exergy approach is shown through the parameters and diagrams presented. Including exergy assessment in building energy codes would be a very important step towards a more energy efficient built environment and would help bringing the exergy approach to the public and decision makers. Therefore, at the end of this chapter, a proposal on how to include exergy in energy codes is suggested.

5.1 Parameters for exergy performance

5.1.1 Quality factors

As stated in chapter 2[23], quality factors are defined as the ratio between the exergy and energy of a given energy system. From a thermodynamic point of view, they represent the proportion of work that can be obtained from an energy conversion process which brings an energy system into equilibrium with its environment[24] as related to the energy input in the process.

Thermal, chemical exergy, mechanical, potential or kinetic exergy derived from different temperature, composition, pressure, height or velocity between a system and its reference environment might be present. Following, quality factors related to all these exergy flows can be derived.

Equation 5.1 shows the general expression of quality factors which can be applied to any energy flow or source.

$$F_{Q_i} = \frac{Ex_i}{En_i} \tag{5.1}$$

However, this report, as well as the method introduced in chapter 2, focuses on thermal exergy. The most popular expression of quality factors for thermal energy transfers are Carnot factors (or Carnot efficiencies). Carnot factors can be applied if an isothermal heat flow happens via a heat engine between two temperature levels. Equation 5.2 shows the expression of Carnot factors for a temperature T of the system and a reference temperature T_0. Carnot factors are used to calculate the so-called "exergy of heat" (see section 2.1.3. in chapter 2).

$$F_{Q,Carnot} = 1 - \frac{T_0}{T} \tag{5.2}$$

However, if the heat transfer is not isothermal, as it is the case for e.g. storage processes Carnot factors cannot be applied. Instead, the quality factor shown in equation 5.3 needs to be used[25]. The quality factor defined in equation 5.3 allow obtaining the so-called exergy of matter (see section 2.1.7).

$$F_{Q,matter} = \left(1 - \frac{T_0}{(T - T_0)} \ln \frac{T}{T_0}\right) \tag{5.3}$$

Quality factors represent the convertibility of an energy flow into mechanical work, i.e. high valued energy with high exergy content. Thereby they allow characterising and distinguishing high exergy sources and demands from low exergy sources and demands. They enable a simple but thermodynamically correct representation of the matching in the quality levels between energy supplied and demanded, and are used for this purpose in the "arrow diagrams" presented in section 5.3.1.

5.1.2 Exergy efficiency

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 identifying the magnitude and point of exergy destruction (Cornelissen, 1997) within an energy system. Therefore they allow to quantify how close a system is to ideal performance or where the energy and exergy inputs to the system are better used (Torío et al., 2009).

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). In (Schmidt and Torío, 2009; Torío et al., 2009) a discussion on the differences and suitability of these two efficiencies can be found.

The mathematical expressions of the simple and rational exergy efficiencies are shown in equations 5.4 and 5.5.

$$\Psi_{simple} = \frac{Ex_{out}}{Ex_{in}} \quad (5.4)$$

$$\Psi_{rat} = \frac{Ex_{des,out}}{Ex_{in}} \quad (5.5)$$

The main difference between both exergy efficiencies is the way the exergy output is considered. The rational efficiency considers the difference between "desired output" and any other kind of outflow from the system. In turn, the simple exergy efficiency considers any kind of output as such, be it desirable or not for the investigated use. In most building systems undesirable outputs are present, e.g. in a waterborne heat or cold emission system in a building, outlet water flows back via return pipes into the heat/cold generation system. In consequence, the simple exergy efficiency works better when all the components of the incoming exergy flow are transformed into some kind of useful output. In turn, the rational efficiency shows how much exergy is getting lost while providing a specific output. Exergy losses regarded in the rational efficiency are due to both irreversible (not ideal) processes present and to unused output exergy flows. Therefore, it is a more accurate definition of the performance of a system and can be better used without leading to false conclusions.
The rational exergy efficiency is the parameter used in the "PER-Exergy efficiency" diagram presented in section 5.3.2 to characterise the exergy performance of community supply systems.

Depending on whether the exergy efficiency refers to a single component or process of an energy system, or whether it refers to all processes and components constituting the system, so-called "single" and "overall" exergy efficiencies can be defined.

An example of single and overall efficiencies for the room air subsystem and complete energy chain in Figure 2.10 (in chapter 2) is given in equations 5.6 and 5.7. Overall efficiencies are derived from an input/output approach[26] for the analysis of a given energy system and can be calculated as the product of the single efficiencies of the single processes or components comprising the system (Torío et al., 2009).

$$\Psi_{single,r} = \frac{Ex_{in,env}}{Ex_{in,ra}} \quad (5.6)$$

$$\Psi_{ove} = \frac{Ex_{out,env}}{Ex_{in,prim}} \quad (5.7)$$

5.1.3 Exergy expenditure figure

To show clearly the relation between the exergy required for supplying a given energy demand, and the energy demand itself Schmidt, et al. (2007) defined the "exergy expenditure figure". Exergy expenditure figures can be used to characterise the performance of components in energy supply systems. This figure can be seen as an enhanced version of the quality factors (exergy to energy ratio), where both the energy and exergy losses in a certain energy conversion unit are depicted.

In equation 5.8 the exergy expenditure figure is defined for a component i of an energy system. It is calculated as the ratio between the exergy input (effort) required to supply a given energy demand and the energy demand itself (use). Auxiliary energy for operating the component is also included as input (i.e. effort) in the parameter.

For supplying a given energy demand due to inefficiencies in the supply systems a greater amount of energy needs to be supplied. Ideally, however, the energy supplied should have a similar quality as the demand. Providing smaller amounts of energy with higher quality would not be sufficient. Therefore, in the exergy expenditure figure the "use" of a given component (e.g. heat loads to be supplied by radiators in buildings) are regarded in terms of energy and not in exergy terms.

Comparing the exergy expenditure figure to the quality factor of the demand provided (use) the level of matching between the quality levels of energy supplied and demanded can be obtained.

$$\varepsilon_i = \frac{Effort}{Use} = \frac{Ex_{in,i}}{En_{out,i}} = \frac{F_{q,in,i}}{\eta_i} + \frac{P_{aux}}{En_{in,i}\eta_i} \quad (5.8)$$

Figure 5.1 shows the energy and exergy flows used for the general definition of the exergy expenditure figure for a component i.

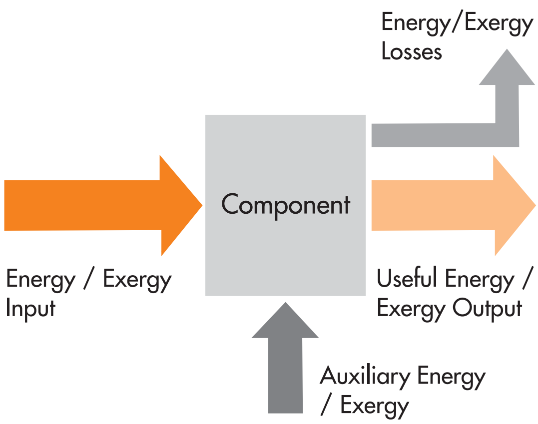

Figure 5.1:Graphical representation of the exergy flows included in the exergy expenditure figure for a general component of an energy system (Schmidt et al., 2007).

Energy and exergy losses happening in the component are implicitly taken into account by the ratio of provided output to required input. Energy losses are taken explicitly into account by means of the energy efficiency in equation 5.8 ηi. Exergy losses are taken into account by comparing the exergy expenditure figure of the component with the quality factor of the final demand to be provided. 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 (see equation 5.8).

For the particular application of space heating and cooling of buildings, the quality factors of the energy demanded are very low. Figure 5.2 shows that for space heating applications assuming an ambient temperature (i.e. reference temperature) of 0°C and an indoor air temperature 21°C the quality factor of energy demand is 7%. Therefore, for space heating of buildings, the closer the exergy expenditure figure for a given system to 7%[27], the better the system exergy performance is. Consequently, in space heating and cooling applications, energy supply systems with low exergy expenditure figures shall be used.

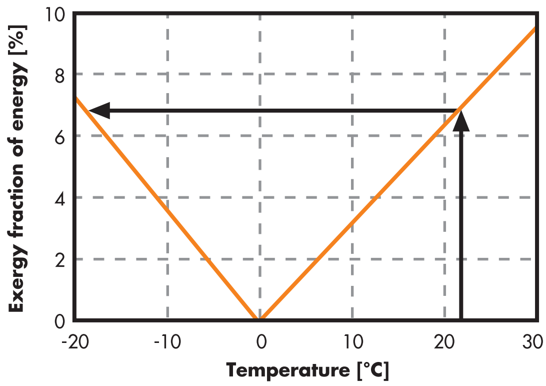

Figure 5.2: For a reference temperature of 0°C, the exergy content of the energy in the room air, assuming an indoor air temperature of 21°C, is 7%.

The definition of the exergy expenditure figure used here is not equivalent to that in the German Standard (DIN 4701-10, 2001), despite similar nomenclature. The main difference is that the exergy expenditure figure as proposed here represents a ratio between an energy output and an exergy input. In the German Standard the energy expenditure figure is the inverse of the energy efficiency of a given component, i.e. a ratio between the required input and the provided output.

The exergy expenditure figure regards the quality level of the energy supplied (effort), whereas the output (use) is regarded in energy terms (i.e. quantity). Therefore, as long as a certain energy source with its corresponding quality level is used with the same energy efficiency, the exergy expenditure figure would be the same and the parameter will not vary. By comparing the exergy expenditure figures for different steps or subsystems of the energy supply to the exergy level of the energy demand (e.g. 7%) the suitability of each component for that particular use can be checked. Therefore, it is a better indicator of the good matching between the quality level of the energy used by a given component and the final energy demand, i.e. of the suitability or appropriateness of the energy system for providing a given use. In (Schmidt and Torío, 2009) a case study comparing the exergy expenditure figure and the single exergy efficiency for different components of the energy supply chain is presented. Results showed the suitability of the exergy expenditure figure for providing insight on the appropriateness of using a given component for a certain energy use (e.g. see Figure 5.3)

5.1.4 Primary energy ratio, PER

Exergy assessment provides information on the matching between the quality levels of the energy demanded and supplied. It allows a common and scientifically grounded approach for analysing different energy sources, be they renewable or fossil. In turn, exergy does not provide any information on the renewability of a certain energy source. To link these considerations with exergy analysis a further parameter is required. Here, the primary energy ratio (PER) is used for this purpose.

PER is calculated as the ratio between the useful energy output, i.e. the energy demand to be supplied, and the fossil energy input required for its supply. The analytical expression of PER is shown in equation (5.6). High PER values indicate that the proportion of fossil energy in the supply is low, thereby meaning that a greater share of renewable energy sources is present in the supply.

$$PER_i = \frac{En_{out,i}}{En_{in,fossil,i}} \qquad (5.9)$$

PER ratios are used in the PER-Exergy efficiency diagram introduced in section 5.3.2 for characterising the performance of community systems.

5.2 Exergy benchmarking proposal for components and building systems

5.2.1 Benchmarking for components of building systems

The exergy benchmarking proposed here for components of building supply systems is based on the exergy expenditure figure (see section 5.1.3). Here the benchmarking method and its applicability are presented by means of an example where several building systems are analyzed.

The case study consists on a building heating case. Several building systems are considered for supplying the space heating demand. In particular, different heat generation and emission systems are regarded: condensing boiler (Cond. in Figure 5.3) without and with solar thermal systems, wood pellet boiler (Wood. in Figure 5.3), ground source heat pump (GSHP in Figure 5.3), district heating (DH in Figure 5.3), radiators (radiator in Figure 5.3) with supply and return temperatures of 55/45°C and floor heating systems (floorh in Figure 5.3) with supply and return temperatures of 28/22°C, respectively.

A component, e.g. a radiator, is designed to supply a specified heating power. An appropriate building system should perform this task with the smallest possible amount of exergy input. Furthermore, the use of high quality (auxiliary) energy, e.g. electrical power, and losses to the environment, should be low.

As described in section 5.1.3 the exergy fraction of the energy needed to heat a room is only around 7%. This value can be directly compared with the exergy expenditure figures of the building service systems discussed above (Figure 5.3). Heat generators that utilise a combustion process use much more exergy than required, and are thus less efficient from an exergy perspective. On the side of the emission systems, the radiator system uses more exergy than the floor heating system, which is closer to ideal in terms of exergy use.

5.2.2 Benchmarking for buildings

All parameters presented until now in this chapter represent different ratio between effort invested and use obtained. In consequence, they state the matching level between energy supplied and demanded, but do not give any information on the total energy or exergy demand of a building. For benchmarking the performance of buildings, similarly as it is done currently in terms of energy, a limitation of the exergy of the primary energy demand is suggested.

An ideal line can be drawn based on the real exegetic demand of the regarded zone. The exergy supplied by different building systems should be compared with the exergy of the demand. Ideally they should be as similar as possible, i.e. for low exergy demands such as space heating or domestic hot water production (DHW) low exergy should be supplied. To promote the use of building systems making use of low quality energy sources, i.e. which require low exergy inputs, the upper limit of the exergy of primary energy input should be limited according to the demand of a good building service equipment solution, similarly as it is done for the limitation of fossil primary energy demands. The limit is set here close to the exergy demand of a condensing boiler, regarded as an available and energy efficient state-of the art technology.

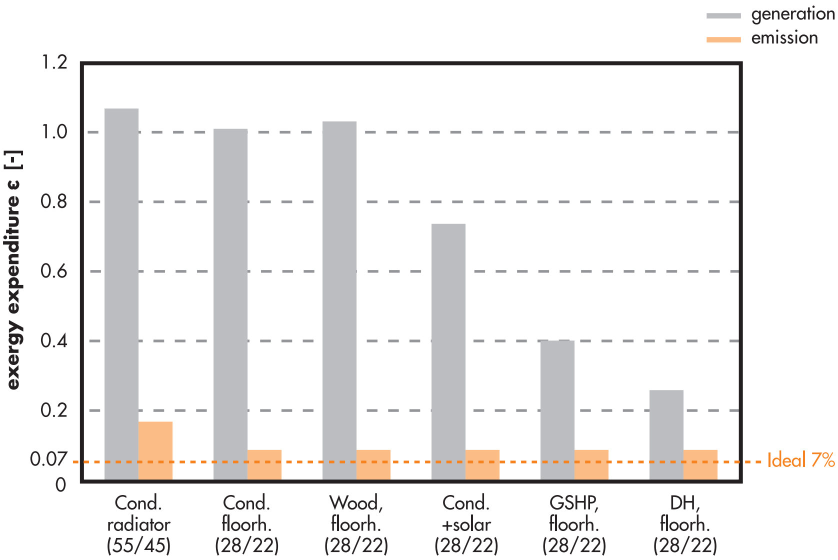

Figure 5.3: Assessment of the components "heat generation" and "emission system" with the exergy expenditure figure for the chosen variants of the building service system.

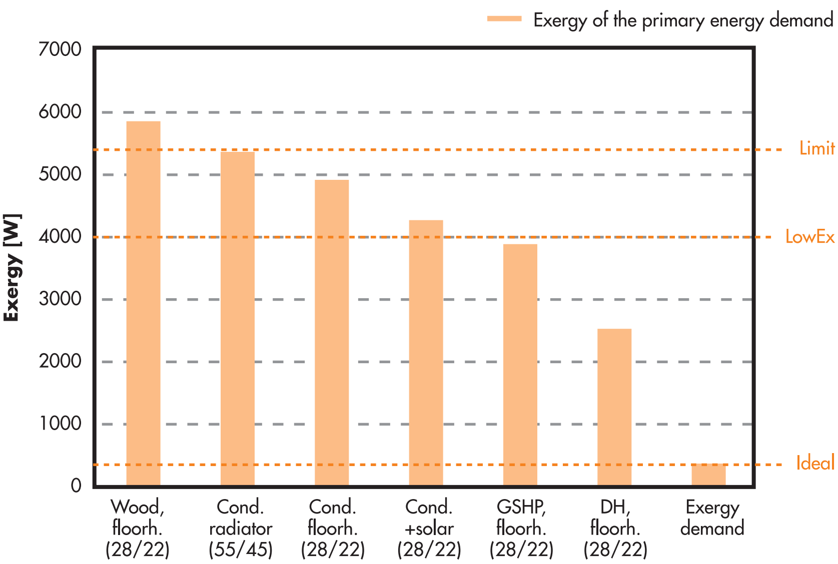

Figure 5.4: Calculated exergy of total primary demand (fossil and renewable) for the chosen variants of the building service equipment (steady state) and a suggested benchmarking classification.

However, it can be clearly seen in Figure 5.4 that a condensing boiler still demands high exergy as compared to the demand. The exergy input can only be reduced if building systems which do not use combustion process to provide low temperature heat are used.

As the supply matches the needed demand and the exergy destruction in the regarded building is kept to a limit, the building can be regarded as a "LowEx"-building.

Four main design principles can be extracted from the examples shown in Figure 5.4:

- The limitation of the primary energy demand is a useful tool to reduce energy consumption and the related CO_2-emissions from buildings. The exergy approach needs to be combined with the primary energy approach in order to include insight on the renewability of energy sources used. This is already mandatory in a number of European countries (e.g. Germany).
- Maximal heat transmission losses through the building envelope should also be limited (e.g. as it is done in German regulations by limiting the mean transmission heat loss coefficient) in order to ensure a good building envelope construction. The energy demand should be reduced. Thereby exergy demands would automatically be reduced.
- To assess and use properly the thermodynamic potential of the utilised energy, the exergy demand of fossil and renewable sources should be limited. This limitation could be done in a similar manner as already known from the procedure of limiting the primary energy demands.
- The exergetic demand of a zone should be satisfied with a suitable supply system, e.g. the exergy expenditure figure should be oriented to the actual exergetic demand of the zone.

5.2.3 Exergy fingerprint diagram

The "Exergy fingerprint" diagram depicts the energy demanded and supplied against the quality of each energy demand (Jentsch et al., 2009)[28]. It allows a quick graphical overview on the matching between the quantity and quality levels of the energy supplied and demanded. The calculation algorithm corresponds to a steady-state approach similar to that implemented on the Annex 49 pre-desing tool (see chapter 3). The diagram is shown here for completeness but has not been used to characterise the case studies from ECBCS Annex 49 work.

Figure 5.5 shows an example of two exergy fingerprint diagrams, for two different energy supply scenarios. The grey areas represent exergy losses in the energy supply. The colours represent the different energy demands considered: electricity, lighting, process heat, DHW and space heating, respectively. The length of the coloured areas (its value on the X-axis) represents the share of the respective energy use on the whole demand. Its height (i.e. its value on the Y-axis) represents the quality of the given demand, i.e. its quality factor. By the mere definition of quality factors (see equation (5.1) with the product of the quantity of the energy demand (i.e. value on the X-axis) and its quality (i.e. value on the Y-axis) the exergy associated to the energy demand can be obtained.

Exergy losses, associated to the energy losses present in the energy supply systems used, are shown at the right of the diagram for the different energy demands analyzed.

Figure 5.5 (a) shows the diagram for a reference scenario consisting of an average residential building in Germany whose demands are supplied with electricity from the German network and a gas condensing boiler.

By comparing the diagram of different supply options with this reference scenario, improvements can be recognized. An ideal supply system would imply firstly a reduction of the demands, i.e. of the length of the coloured areas (on the X-axis). Furthermore, exergy losses, i.e. grey areas, also need to be reduced. An improved insulation level for the building shell and the use of suitable energy supply systems, such as CHP units and waste district heat, allow achieving these aims as shown in Figure 5.5 (b). The better performance is also shown at a glimpse through the a traffic light complementing the diagram, where the exergy savings in percentage as compared to the reference scenario can be read.

The diagram gives similar information as that delivered by the Annex 49 pre-design tool. However, the performance of the different components in building supply systems cannot be assessed individually with this diagram. The Annex 49 pre-design tool allows to obtain such information on a quick and easy way. Different building energy demands (e.g. DHW, space heating or lighting) are also included in the tool.

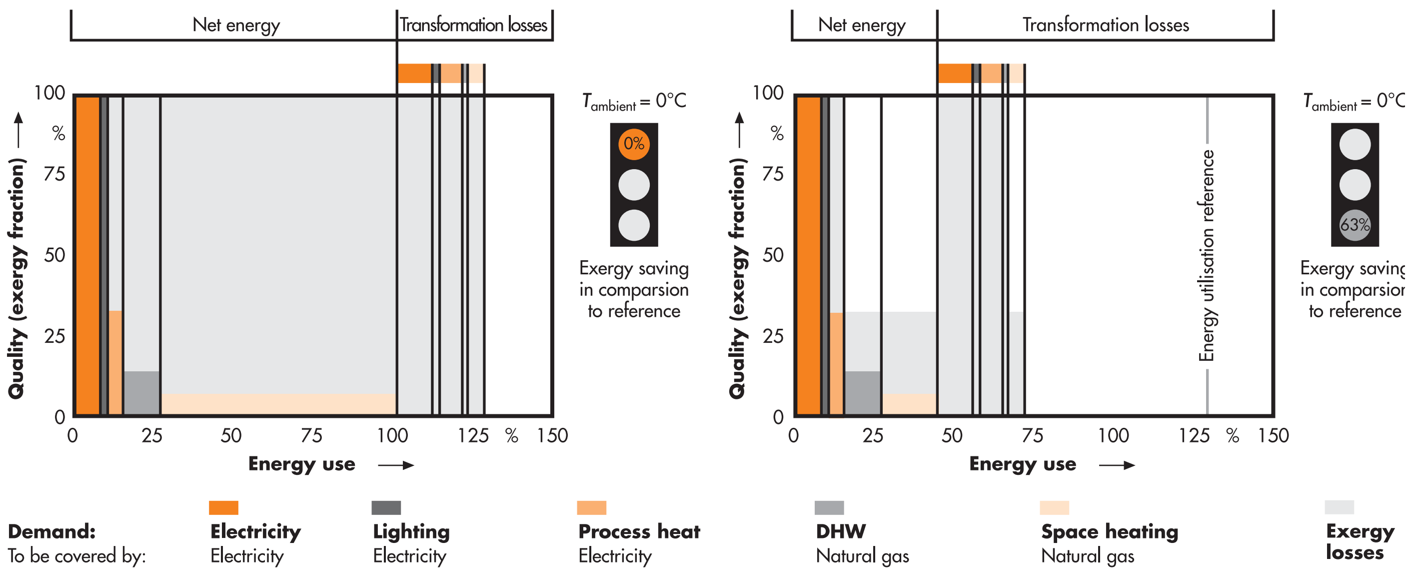

Figure 5.5: (a): Exergy fingerprint diagram for a reference scenario consisting of an average residential building with an energy supply via a gas fired condensing boiler; (b): Exergy fingerprint diagram for an improved scenario consisting of a well insulated building supplied with CHP units and district heating[28].

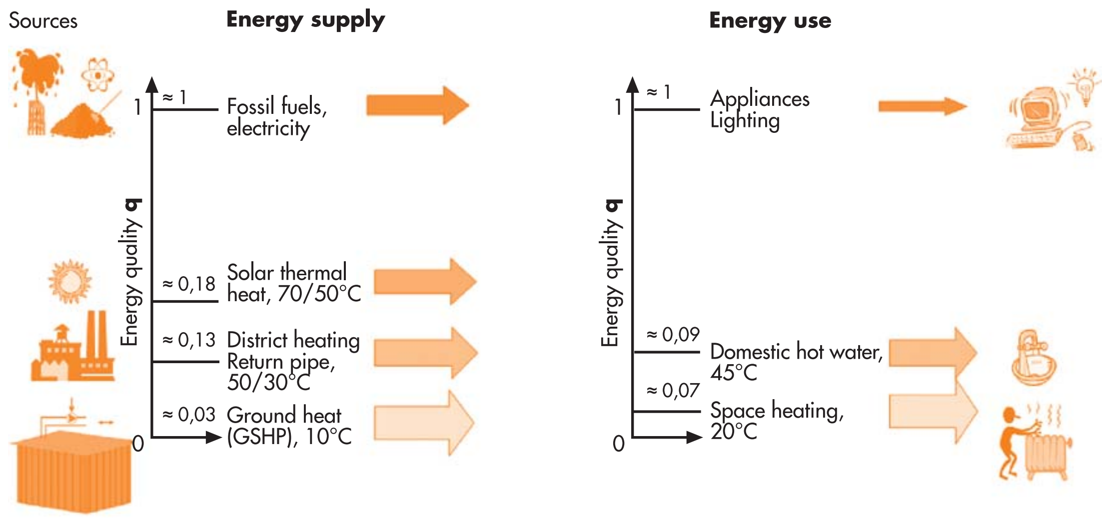

Figure 5.6: Example of an arrow diagram.

5.3 Graphical representations for characterising the exergy performance of community supply systems

Graphical representations for characterising the exergy performance of community supply systems enable to visualize the performance of a given case study and make different community energy supply concepts comparable. The characterisation of the exergy performance of different case studies and community concepts is presented here by means of different diagrams included under the section "LowEx Diagrams" in the respective case study (see chapter 7).

5.3.1 Arrow diagrams

The arrow diagram[29] shows the matching between the quality levels of the energy supplied and demanded. The diagram is a qualitative representation of the quality and quantity of energy demands and supply in buildings. Figure 5.6 shows an arrow diagram as an example.

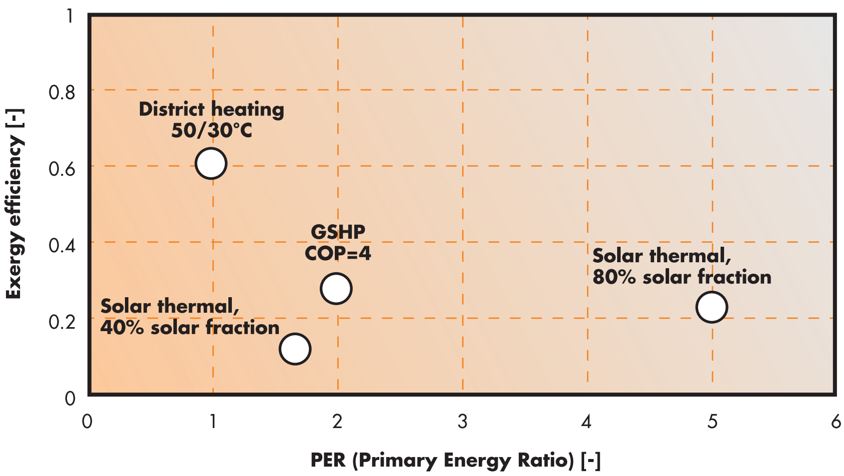

Figure 5.7: Example of an "PER – exergy efficiency" diagram.

The position of the arrows on the Y-axis (i.e. "Energy quality, q", with a scale from 0 to 1) represents the quality factor of the energy supplied and demanded and thereby depicts the exergy content of the energy flow. The thickness of the arrows represents the amount of energy demanded or supplied. By these means both the quality and quantity of the different regarded energy flows is shown. Thus, similarly as the exergy fingerprint diagram introduced in the previous section, the matching between the quantity and quality levels of the energy supplied and demanded can be seen.

5.3.2 PER – Exergy efficiency diagram

The Primary Energy Ratio (PER)-Exergy efficiency diagram[30] characterises the exergy performance and use of renewable energy in the supply of a community project. Exergy efficiency is represented in the Y-axis. PER ratio is represented in the X-axis. Each case study is represented by both factors (white dots in the diagram). Ideally, high values for the exergy efficiency and PER ratio should be obtained. White dots show both parameters for different supply concepts, characterising the performance of the case study. Dots in the upper right corner indicate good exergy performance and high use of renewable energy sources. Supply concepts on the area close to the upper right corner would correspond to "LowEx" community concepts. In turn, dots close to the lower left corner depict case studies with low exergy efficiency and high fossil fuel share on the energy supply.

5.4 Pre-normative proposals

Buildings are major contributors to the final energy demands in many industrialized countries (Eurostat, 2007). Therefore, to reduce CO_2 emissions from the built environment and thereby contribute to a more sustainable development and to international targets trying to limit climate change, energy directives for buildings have been developed.

Generally all current energy laws are based on energy (i.e. the first law of thermodynamics), not on exergy. In these sections some thoughts and suggestions on including the exergy concept in energy legislation are presented.

There are five important questions to be asked when designing energy legislation:

- Which objectives are to be obtained by this legislation?
- Which parameters are the right indicators of the (energy) performance the building in relation to the foreseen objectives?
- Which analysis method should be used?
- Which 'requirements' should be set to the building? (e.g. benchmarking against comparable buildings or set a maximum value to the chosen parameters)
- Which administrative instrument could best be utilized? (i.e. energy tax, 'force', subsidies)

The following section gives a brief introduction to current European energy legislation and tries to give some thought and suggestions on including the exergy concept, hereby also addressing the five questions mentioned above.

5.4.1 Current status of energy laws

Reducing energy consumption and eliminating waste are among the main goals of the European Union (EU). There is significant potential for reducing energy demands, thereby limiting consumption of energy sources. With nearly 40% of the energy consumed in buildings, the EU has introduced legislation to implement energy efficiency measures in the built environment. According to the Energy Performance Building Directive (EPBD, 2002) the Member States must apply minimum requirements as regards the energy performance of new and existing buildings, ensure the certification of their energy performance and require the regular inspection of boilers and air conditioning systems in buildings (EU, 2010). Regarding the five main questions raised in the previous section, the following answers can be given related to current energy legislation on a European level:

- Objectives: the final aim is to promote secure and sustainable energy supply systems for the built environment. Related to sustainability this objective is translated to the aim to reduce primary energy use and CO_2 emissions. This objective should be obtained by reducing energy demands in buildings and enhancing the use of renewable energy sources within the sector.
- Parameters: the secondary objectives formulated above already determine primary energy use and CO_2 emission as indicators for the performance of a system.
- Method: The analysis method must be determined by the member countries. However, it should be according to some defined standards to allow certain comparability and based on common framework methodology for all member states. It is also mentioned that "the calculation shall also include a numeric indicator of carbon dioxide emissions and primary energy use" (van Dijk, 2008).
- Requirements: the Member States are responsible for setting their own minimum thresholds and benchmarks.
- Administrative instrument: compulsory energy performance certificates should be made available when buildings are constructed, sold or rented.

5.4.2 Including Exergy in energy legislation

As it can be concluded from the previous paragraph there are no exergy requirements (using exergy as a methodology or as an indicator) in current energy legislation.

Some literature about including exergy in energy legislation (Van Gool 1997; Dincer 2002; Favrat et al., 2008) can be found. These works mainly focus on the importance of including exergy in energy legislation. Favrat et al. (2008) describe a practical approach determining fixed exergy efficiencies for various energy conversion processes. In this work it is also mentioned that the Canton of Geneva (Switzerland) requires that documents from city developers include an exergy performance evaluation of their project.

In this paragraph the main motivation and contribution gained by including exergy in energy legislation is presented and findings form the previous chapter are summarised. The same structure used in the previous sections is followed:

- Objectives: the main motivation for including exergy in building energy regulations is that this concept can contribute to design and operate more efficient energy supply systems in the sector since exergy depicts the real thermodynamic efficiency (and thereby the improving potential) of energy systems. This could contribute to the main objective of the energy legislations available of achieving more sustainable energy supply systems. In addition, exergy allows analyzing all sorts of energy sources on a common and scientifically grounded basis (be they renewable or fossil). It can be argued that in the future, when all energy supply is based on renewable energy, it will also be important to use renewable energies in an efficient way, since they are limited in time or space, and the conversion of energies will never be free of materials. Therefore it can be argued that a secondary objective can be to reduce exergy destruction by designing more intelligent systems, even if these are based on renewable energies.

- Parameters: exergy is in the first place related to the thermodynamic performance of a system[31]. An exergy analysis can, therefore, determine how much potential has been lost and thus how well the performance of an energy supply system really is, compared to the ideal performance. In this way exergy has an added value to energy:
  - Exergy efficiency always <100% (different from COP), thus a real improvement potential can be determined, while energy analysis is only able to compare systems;
  - Exergy analysis shows quality losses that are not shown with energy analysis, being thereby a true measure for the thermodynamic efficiency and performance of a given system or process;
  - Exergy assessment is not limited to the consumption of "primary energy" as in energy from fossil fuels (as the primary energy approach is), but it also includes the analysis of the potential of renewable energy sources used. Therefore it is also a tool to design intelligent systems using renewable energies.

- Method: using exergy analysis as a method to determine the exergy losses and the improvement potential is the most obvious application of the exergy concept, which is already used by many designers of energy systems. An exergy analysis can support meeting the objective to reduce the consumption of primary energy sources by making available more efficient building systems. Furthermore, by matching the quality, i.e. exergy, level of the energy supplied and demanded suitable energy sources and energy systems can be identified for providing different uses with different quality levels within the built environment (e.g. space heating and lighting). At this moment no standard tool at the level of most national energy analysis tools is available. A first idea of the exergy performance can be obtained with the Annex 49 pre-design tool (see chapter 3, section 3.2). Alternatively the calculation methods as explained in chapter 2 can be applied. The development of a generally applicable tool as are the current energy tools, will require additional work.

- Requirements: since exergy analysis is relatively new in the built environment it is difficult to set minimum standards at this moment. By now, a common scientifically grounded methodology has been developed and agreed upon by the ECBCS Annex 49 group (see chapter 2). The next step would be to apply the methodology to several case studies and define benchmarks based on the results. For a first idea the paragraph on benchmarking (section 5.2) can be considered. In addition, requiring an exergy analysis as is done by the Canton of Geneva (Favrat et al., 2008) can be a good first step, since this will give insight in the losses and motivate designers to come up with more intelligent systems. It is also a way of introducing the concept to many professionals working in the built environment.

- Administrative instruments: once the benchmarks are set, administrative instruments to make sure that they are met can be defined. However, as stated above, further research needs to be conducted to reach this stage. Thus, the discussion of possible administrative instruments is not further treated in this work.

5.4.2.1 Exergy as sustainability indicator

Sustainable development can be defined as a development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (Bruntland, 1987). Several authors have linked the exergy concept with insights on sustainable energy supply and sustainable development (Cornelissen, 1997; Rosen and Dincer, 2007; Wall and Gong, 2001). This link is based on the fact that exergy is a thermodynamic concept that clearly identifies the improvement potential of an energy system, thus opening up the possibility of increasing its efficiency (Rosen et al., 2008). For this aim, all energy flows involved, fossil and renewable, must be analyzed. This allows showing the thermodynamic efficiency of using different energy sources, independently of their renewable or fossil character, and allows a common basis for the comparison of different energy sources and uses (Schmidt et al., 2007). Since energy sources, and particularly fossil fuels, are limitedly available, increasing the efficiency of their utilization leads to increase the time span in which they can be utilized and reduce negative environmental impacts derived from its use, thus increasing "sustainability" of energy systems.

However, it must be clearly stated that systems based on renewable energy sources are more "sustainable" than fossil fuel based ones, even if the exergy efficiency of the first might be lower than that of an equivalent fossil-based alternative. The exergy concept does not distinguish between renewable and not renewable energy sources. This distinction, crucial for finding options towards a more "sustainable" energy supply, must always be regarded additionally to the exergy analysis.

Therefore, within research group of ECBCS Annex 49 consensus was agreed upon that exergy can NOT be understood as an indicator able to depict sustainability on its own. Exergy performance and sustainability are not equivalent concepts, and exergy analysis can only be seen as a further indicator to complement existing analysis methods in order to develop more "sustainable" energy systems.

5.5 Main conclusions

Several parameters usable to depict the matching of the quality levels between the energy supplied and demanded have been introduced. Through their application to case studies it has been shown that exergy analysis adds information to conventional energy analysis: the supply of high quality exergy in buildings for space heating and DHW supply purposes needs to be minimized. This implies avoiding burning processes in building supply systems and substituting them by low temperature systems and sources. In consequence, the core of the benchmarking proposal is to minimize the exergy of primary energy supply. With the parameters and benchmarking proposal presented in this chapter, this information is made directly and clearly available to building planners on a scientifically grounded basis.

In section 5.2.2 guidelines based on the exergy benchmarking proposed and additional to those derived from common energy assessment can be found.

Additionally, exergy analysis provides a commonly and scientifically grounded base for comparing energy systems using different energy sources, renewable and fossil, giving a true measure of the efficiency of their performance. In this sense, exergy analysis contributes to promote the efficient use of renewable energies. Since they are limited in time or space, and the conversion of energies implies also material use and process, reductions in the exergy destruction contributes to design more intelligent and efficient energy systems, even if these are based on renewable energies.

It is important to remark that, despite the great added value of exergy, it cannot depict the "sustainability" of an energy system.

Thus, including exergy analysis in energy legislation is useful for two reasons: it supports meeting the objective to reduce primary energy consumption, and it supports the design of intelligent energy supply systems based on renewable energy, which will also become important in the future. The practical implication as to standardised methods and minimum requirements must be further developed. However, the methodology presented in chapter 2 of this work and results from case studies presented in chapters 6 and 7 can be a very valuable contribution for this purpose.

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[23] The formal definition of quality factors can be found in section 2.1.4.

[24] so-called "reference environment", see chapter 2.

[25] Quality factor in equation 5.2 corresponds to a thermal heat transfer where the temperature of the system changes from T to T_0 reversibly, i.e. via several heat engines working respectively at temperatures infinitesimally small than T (i.e. $T-dT$; $T-2dT$; etc.) until T_0.

[26] A detailed description of this input/output approach can be found in section 2.2.1 in Chapter 2.

[27] For cooling systems the quality factor of the demand to be provide is even lower due to the closer temperature level to outdoor air.

[28] This diagram has been kindly supplied by the research group from the Fraunhofer UMSICHT Institute (Germany).

[29] The diagram has been developed by VTT (Finland).

[30] The diagram has been developed by CHRI, Cauberg-Huygen (the Netherlands).

[31] By some authors (Wall and Gong, 2001) exergy is also used as an environmental indicator, meaning it is also a measure for sustainability in a broader sense than just 'reducing energy consumption''. However, this vision is not supported by the Annex 49 group, as it is clearly stated further below in this chapter (see section 5.4.2.1).

6. APPLICATION OF THE EXERGY APPROACH TO BUILDING SYSTEMS

In the present chapter, several building case studies are shown where the general exergy-based design strategies for buildings presented in chapter 4 are applied. Emphasis is put on the reduction of energy use by means of innovative approaches for cold and heat storage as well as energy recovery. Six case studies of innovative concepts or technologies are presented here. A more extended collection of technologies (but less detailed and innovative) can be found at (Ala-Juusela 2003). Three of them are related to air-conditioning systems, in order to reduce both the energy required for cooling and for the air circulation to ensure proper indoor air quality. The need for cooling, in fact, is becoming increasingly high in buildings: since there are less alternatives for producing cold than for heat generation – cold is commonly produced with air heat pumps with relatively poor efficiency – the possibility of using natural ventilation or evaporative cooling would be beneficial.

Similarly to the seasonal storage systems, ground heat helps improving the performance of the building system by using a renewable and freely available source: its exploitation is particularly interesting with heat pumps, raising their COP to a value that makes the use of a high exergy source like electricity convenient. The use of hybrid technologies, coupling the use of renewable and non-renewable energy is in fact one of the most promising trade-off between availability and exergy efficiencies.

Waste heat can be considered another type technology particularly efficient form an exergy point of view: its use in the cogeneration approach is now widespread but it has to cope with problems like the matching of heat and electricity demand in the power plant, the need of an extensive planning and energy loss due to the heat distribution. An innovative approach that would partially solve these issues is the local heat recovery in the building, as it will be shown in the before last case study (see chapter 6.6).

Two cases are about seasonal storage systems both for cooling and for heating (see chapters 6.4 and 6.5). They are mandatory for an effective exploitation of renewable sources but they are also useful to lower the peaks in the supply system and to make it work preferentially in the best possible conditions. By letting the demand and the supply not being directly matched, they pave the way for a flexible energy use management.

A further case is about a waste water system to recover heat from buildings waste waters similarly to the heat recovery systems in the Air Handling Units (AHU): a rational energy use, in fact, would comprise the recovery of all valuable types of energy (see chapter 6.6).

The following is the detailed list of the cases presented in this work:

1. Innovative Concepts for Exergy Efficient Air-conditioning Systems and Appliances in Buildings

2. Temperature and Humidity Independent Control (THIC) air-conditioning system

3. Adjustment of the ventilation rates based on the variation in time of the actual needs

4. Seasonal heat storage by Ground Source Heat Pumps (GSHP) system

5. Shallow ground heat storage with surface insulation

6. Exergy recovery from waste water in small scale integrated systems

7. Innovative configuration for cooling purposes: series design for chillers

6.1 Innovative Concepts for Exergy Efficient Air-conditioning Systems and Appliances in Buildings[32]

Main features of the concept

By using outdoor dry air as the driving force, the indirect evaporative chiller aims to give a novel air-conditioning concept for public buildings in dry regions. In this manner, it is taken advantage from the use of "wet" exergy contained in liquid water (which is very large) in order to produce cool exergy and subsequently cool the air or water as a cool carrier.

It produces cold water with a temperature of 15-18°C, lower than outdoor wet bulb and infinitely close to the dew-point temperature of the inlet air. As the heat carrier of the chiller is water not air, the energy consumption for transmission is reduced a lot. An air conditioning system is also designed using the indirect evaporative chiller, as Figure 6.2 shows, which can use outdoor dry air sufficiently by matching the temperature level of the cold water and the heat sources.

Competitiveness

Compared to common mechanical compression refrigeration systems, the indirect evaporative chiller uses natural outdoor dry air as the driving force: up to 50 % energy cost can be saved. As no CFCs are used, related pollution is avoided. Compared to common indirect evaporative cooling systems, this chiller uses water as energy carrier and therefore the power cost for transport of the cooling energy can be largely reduced. Besides, it produces cold water with limit temperature being dew point of the inlet air, which is much lower than direct evaporative cooling systems. These benefits expand the application extent of the indirect evaporative chiller.

Side effects

The cold water of this chiller is pumped into room terminals such as fan-coil units or radiant panels. As the water and indoor air come into contact with each other indirectly, the potential water contaminants cannot influence the indoor environment. Besides, since the temperature of the cold water is commonly 16-18 °C, higher than the indoor dew point temperature, no condensation could occur. For the whole

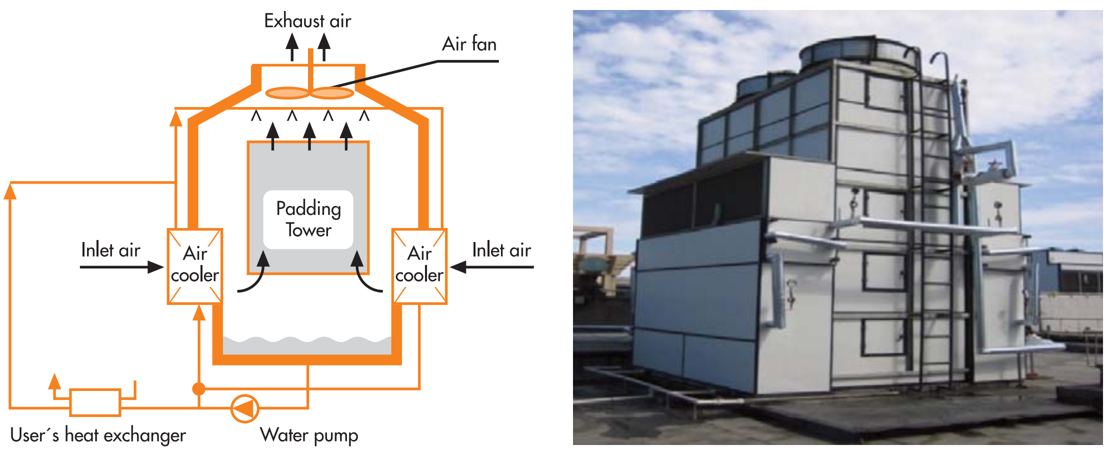

Figure 6.1: Principle of the indirect evaporative chiller (left) and picture of the first developed unit (right).

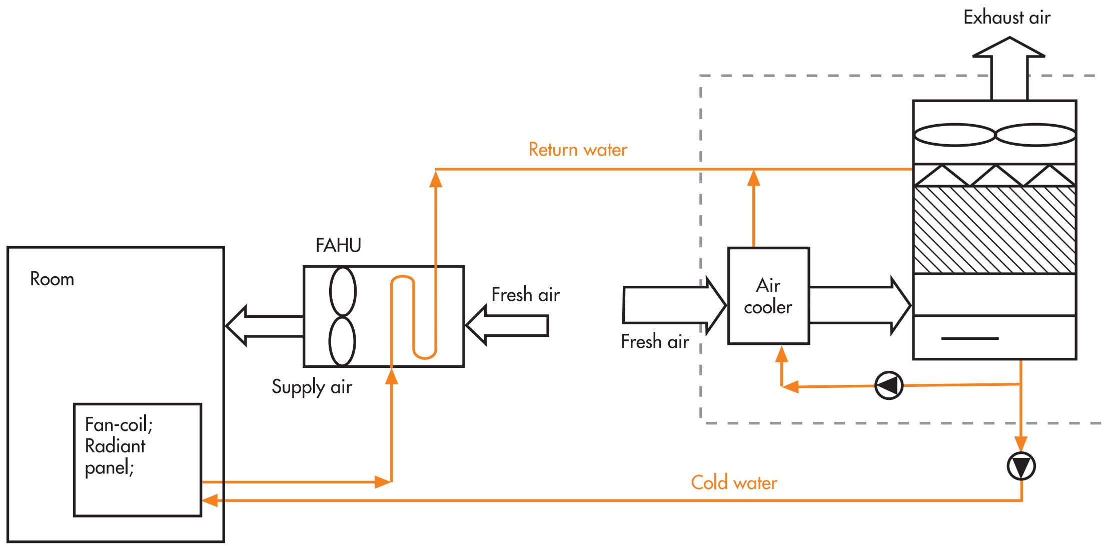

Figure 6.2: Structure of the air-conditioning system using the indirect evaporative chiller

system, as enough fresh air is supplied into the rooms, a healthy indoor environment can be achieved.

Some water needs to be supplemented for evaporation, and with flow rates about 3-5 % of the cycle water flow rate, the evaporative cooling technology is not suitable for regions with an especial lack of water. However, for most of the dry regions in the world, this is not a problem.

Performance analysis tools

The structure of this chiller has been invented and it is patent-protected. The structures of the inside subcomponents were designed and are also patented, such as a quasi-counter current air-cooler and the counter current padding tower. A simulation model was set up using EES (Electronic Environmental Simulator) by which the inside parameters can be maintained under different outdoor conditions. Actual devices have been developed and put into buildings for application. By testing the developed indirect evaporative chiller, the feasibility of this chiller was validated and the real performance of this chiller was gotten.

Testing performances

The first chiller was developed in 2005 and its performances were measured, as Figure 6.3 shows. The outlet water temperature of the developed chiller is lower than indoor wet bulb and more or less at the middle of the dew point and wet bulb temperature. The outlet water temperature is mainly influenced by dew point temperature of inlet air, as Figure 6.4 shows.

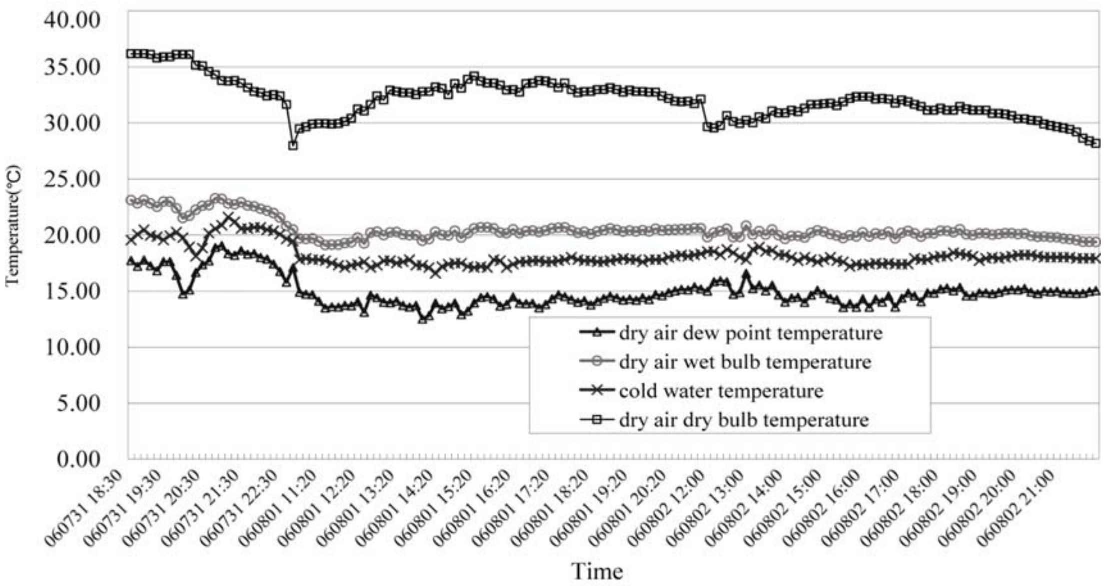

Figure 6.3: Tested cold water temperature.

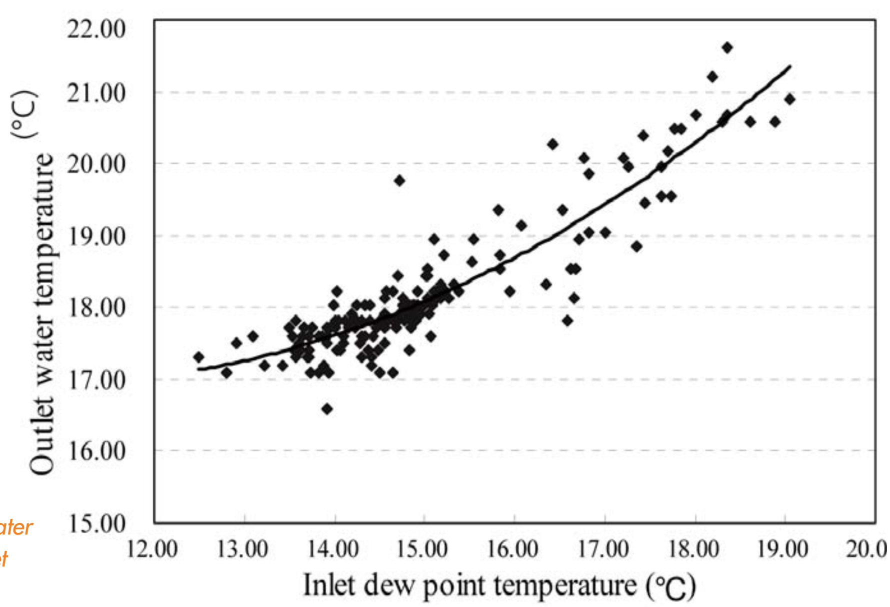

Figure 6.4: Outlet water temperature with inlet dew point.

Demonstration projects
From 2005 to this day, the dry air driven indirect evaporative chiller and its system have been installed in more than 15 projects serving for about 120,000 m² building area, such as Shihezi KaiRui Building, Aksu People's Hospital and the Xin Jiang Hospital of Traditional Chinese Medicine. The installed chillers have been working well and reliably.

There are many regions with dry outdoor climate all over the world, such as Northwest China, Southwest America, most zones in India and Australia, or zones in Europe. In these dry regions, the indirect evaporative chiller can be profitably used, which means that it has a very considerable application potential.

Monitoring results and further information on the projects can be accessed by the following publications (Xie et al., 2007; Xie and Jiang, 2007; Tsinghua University, 2008).

Planned further activities
The applications of this chiller in Northwest China have been carried out steadily, not only in Xinjiang Province, but also Gansu and Inner Mongolia. Chances for popularising this technology in the world are under evaluation.

Internet sites
N/A


Shihezi Kai Rui Building   Aksu People's Hospital   Xin Jiang Chinese Medicine Hospital

Figure 6.5: Demonstration buildings using the indirect evaporative chiller

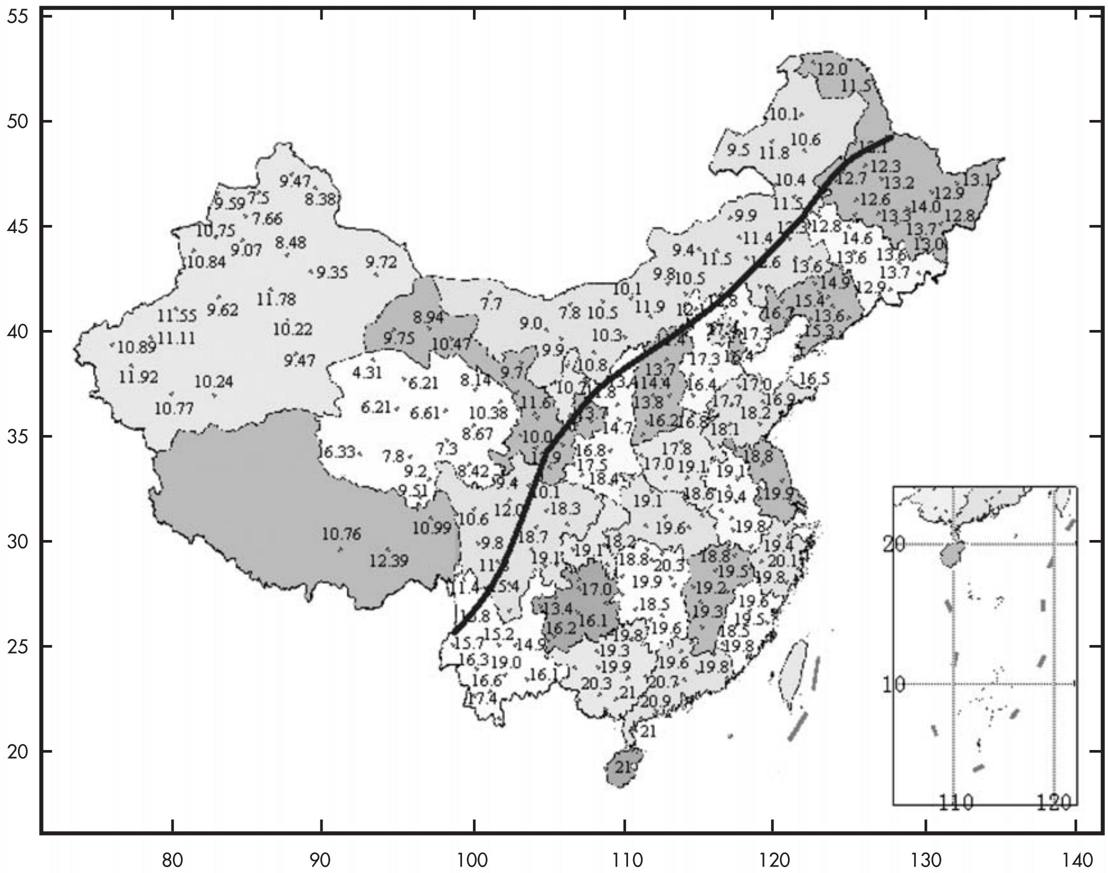

Figure 6.6: Average humidity ratio of the most humid month in China. Southeast of the line: outdoor air is humid. Northwest of the line: outdoor air is dry enough.

6.2 Temperature and humidity independent control (THIC) air-conditioning system[33]

Main features of the concept

Temperature and humidity control are two main tasks of air-conditioning systems. In most centralised air-conditioning systems in China, the air is cooled at the temperature below the indoor dew point temperature, dehumidified by condensation, and then supplied to the occupied spaces to remove both the sensible and latent load. The required chilled water temperature should be lower than the air dry bulb temperature or air dew point, in order to remove the sensible load (control temperature, covers 50%-70%) or the latent load (control humidity, covers 30%-50%), respectively. However, the same 7°C water is used to remove both sensible and latent load and available energy is wasted as a result.

The proposed THIC (Temperature and Humidity Independent Control) system is composed of two separated systems, temperature control system and humidity control system, as shown in Figure 6.7. The temperature of chilled water in the temperature control system is raised from 7 °C in conventional systems to about 18 °C, which allows the utilisation of some natural cooling sources too. Even if chilled water is still produced by a mechanical chiller, the COP (Coefficient Of Performance) will be increased significantly.

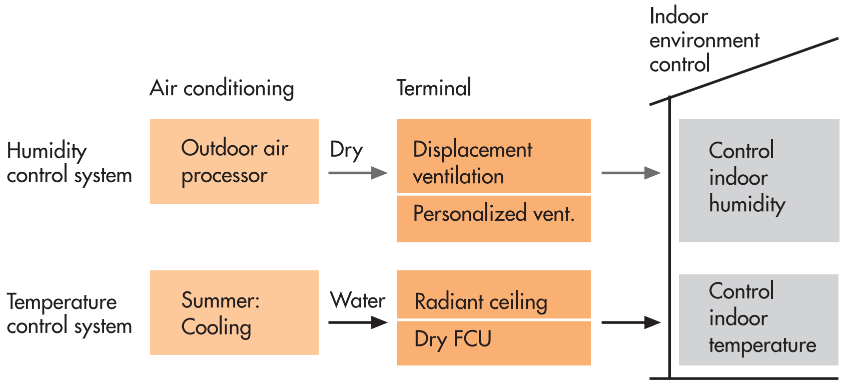

Figure 6.7: Device scheme

In the southeast of China, where many large buildings are located, the outdoor air is humid: the main task of air-conditioning systems is to dehumidify the air. Liquid desiccant dehumidification method is recommended.

In the northwest of China, the outdoor air is dry and the main task of air-conditioning systems is to decrease its temperature. Directly or indirectly evaporative cooling is recommended.

Competitiveness

(1) Humid area in the southeast of China

The recommended THIC system is composed of a liquid desiccant outdoor air processor to control indoor humidity and a refrigerator (chilled water temperature increased to 18 °C) to control indoor temperature. The initial cost of the THIC system is a little higher than the conventional system. The operating cost of the THIC system is only 60%-70% compared to the conventional system. About two or three years are required to recover the extra initial cost. The energy saving potential can be even higher, if a natural cooling source, such as underground water, can be used to control indoor temperature instead of the chiller.

(2) Dry area in the northwest of China

The recommended THIC system is composed of an evaporative cooling outdoor air processor and an indirect evaporative chiller. The initial cost of the THIC system is about the same as for the conventional system. Roughly 50 % operating energy can be saved compared to the conventional system.

Side effects

Improved indoor environment: the indoor humidity as well as indoor temperature can be accurately controlled. Wet surfaces by using liquid desiccant dehumidification method are avoided. An added benefit of the liquid desiccant system is the potential to remove a number of pollutants from the processed air.

Performance analysis tools

A self-developed simulation tool based on Matlab is used to analyse the performance of the main air-conditioning devices, such as the liquid desiccant air-conditioning (LDAC) device and the indirect evaporative chiller (IEC).

Simulation studies

The performances of various types of liquid desiccant outdoor air processors both in summer and winter, indirect evaporative chiller and the THIC system can be simulated. The detailed information can be found in the references (Liu et al. 2006; Li et al., 2005; Xie and Jiang, 2008; Xie and Jiang, 2007).

Demonstration projects

From 2005 so far, over 1,000,000 m² buildings in the southeast of China have adopted liquid desiccant based THIC systems; over 100,000 m² buildings in the northwest of China have adopted evaporative cooling based THIC systems.

Figure 6.8: Map of some of the existing buildings using THIC approach in China.

The detailed monitoring results are shown in the literature (Chen, et al. 2005; Li et al., 2005; Xie and Jiang, 2008; Xie and Jiang, 2007).

Planned further activities

More monitoring building energy use results need to be collected.

Internet sites

N/A

6.3 Adjustment of the ventilation rates based on the variation in time of the actual needs

Main features of the concept

Ventilation plays a role of key significance in the building overall performance in terms of energy consumption, indoor air quality and thermal comfort. Ventilation can be ensured by natural means or by a mechanical system. Uncertainty about practicing a real control on airflows and the unreliability related to the stochastic nature of its driving forces – wind and temperature gradients – are the major challenges to the development of purely natural ventilation technique. Mechanical ventilation may result in an unnecessary energy use. The hybrid technology represents the attempt of combining the benefits of both ventilation strategies in a unique system by promoting the interactions between occupants, indoor climate and outdoor conditions. Hybrid technology urges a technological development of system components (supply inlets, exhaust grilles) and control algorithms in order to make airflow rates always consistent with the actual ventilation needs (e.g. amount of fresh air). The energy required by air conditioning and distribution has also to be minimized.

Side effects

Energy required for ventilation represents great part of the total energy use especially for buildings characterized by high levels of insulation. In former times we used to say that 40 % was ventilation loss but this has probably increased but then reduced again with high performance heat exchangers and good air tightness, Ventilation is of major importance for the well-being of people within enclosed spaces. Building design has to face the dual challenge of providing a healthy and comfortable indoor environment and enhancing low energy use. The hybrid technology represents a mean for achieving a full integration between ensuring acceptable indoor air quality and scoring a good energy performance.

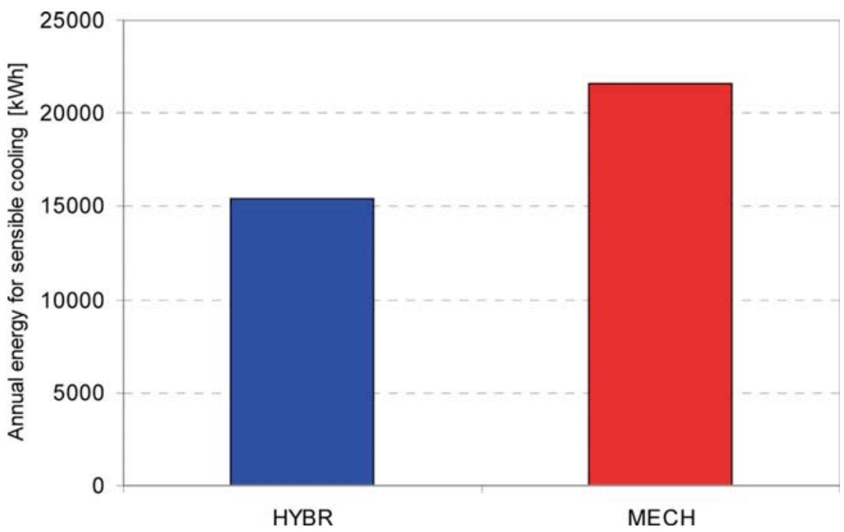

Figure 6.9: Annual hybrid and mechanic energy use for cooling.

Performance analysis tools

Simulations for a building implementing the hybrid ventilation concepts have been performed combining an energy performance model and a ventilation model. The building model has been set up in TRNSYS environment. The building as a whole has been schematized as multi-zone system. Airflow calculations within the building have been calculated by means of CONTAM.

Simulation studies

Studies have been carried out for a building that is planned to become a medical structure. Spaces and related activities are distributed on two floors which are connected vertically by a large central atrium. The ventilation strategy is to meet a maximum allowable CO_2-level for the whole building of 1000 ppm. Airflow rates are consistent with the recommendations of EN 13779 for an IDA 1 indoor environment, i.e. with high indoor air quality, providing a supply of 55 $m^3 h^{-1}$ of outdoor air per person. Ventilation in the zone varies accordingly with its level of occupancy. Winter time operation relies on mechanical ventilation, being based on the maximization of heat recovery. Summer time operation takes advantage of natural ventilation for temperature and CO_2 control as long as it does not represent a risk for comfort. To exert a control on the airflows entering their rooms, patients spaces are equipped with self regulating hygroscopic vents. There are devices that allow airflow depending on the sensed value of relative humidity. If CO_2 level exceeds the threshold level of 1000 ppm, mechanical ventilation is turned on. Figure 6.9 and Figure 6.10 show the comparison between the results obtained by means of the implemented hybrid ventilation system (HYBR) and what could have resulted in the case the fully mechanical ventilation strategy is extended to the whole year (MECH).

Demonstration projects

N/A

Planned further activities

Research activity on the benefits consequent to natural ventilation automatic control techniques is currently ongoing. The objective of the study is to evaluate the potential of natural ventilation to provide airflow rates consistent with acceptable indoor air quality. Natural ventilation will be operated by allowing a control on the airflow rates, such as self regulating vents or window aerators. Systems will rely on control systems that automatically can switch

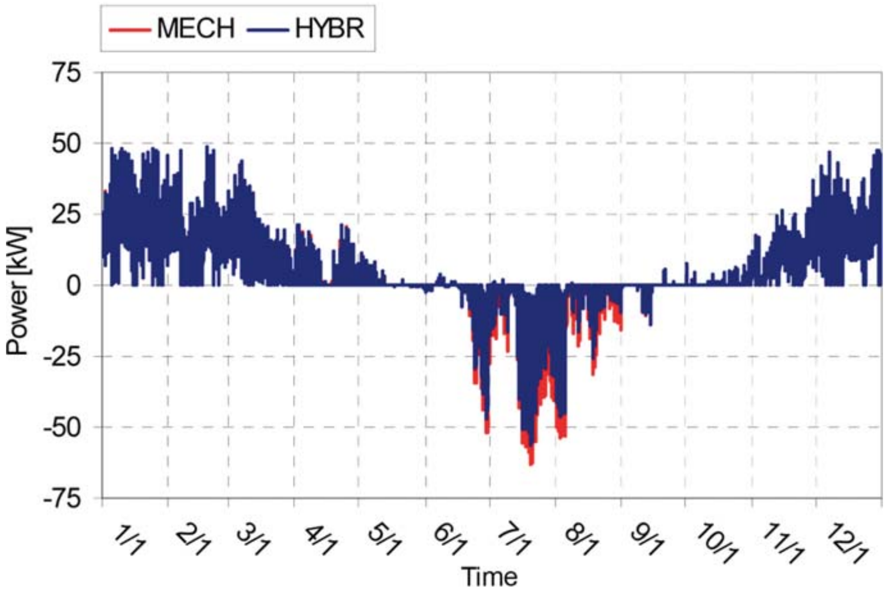

Figure 6.10: Peak power annual use.

between natural and mechanical mode in winter and in periods of poor natural forces or increased demand.

Present evaluation statement (2008-07-09)
Simulations show that it is possible to combine a sustainable low-energy building and, at the same time, to ensure a comfortable and healthy indoor environment (Villi et al., 2008). This system is able to provide occupants with airflow rates consistent with an IDA 1 indoor environment. For about 25 % of the summer time operation period, the exploitation of natural ventilation is able to keep indoor CO_2 concentration below the 1000 ppm threshold level.

Internet sites
N/A

6.4 Seasonal heat storage with ground source heat pump system[34]

Main features of the concept

As already stated in this report ground source heat pump (GSHP) systems with vertical ground source heat exchangers can be an effective solution to heat and cool buildings with low-exergy consumption. In the case of small buildings the tubes are normally installed satisfactorily far from each other and utilise the geothermal energy of the constant temperature of far-away soil volumes. In this way the seasonal energy storage is not available. However, in the case of larger buildings where several boreholes have to be installed, a more effective conception can be used. In this case the tubes can be installed in a cylindrical branch. If the number of boreholes increases, the proportion among the cylindrical boundary surface and the heat storage soil volume becomes smaller. As a result, the heat storage soil volumes are in contact with a relatively smaller surface with the far-away soil volumes. Consequently the effectiveness of the seasonal heat storage becomes higher (see Figure 6.11). In order to decrease the exergy loss of the stored energy (the temperature drop can be decreased), the heat exchangers are distributed into more groups and used in a suitable sequence during the heating and cooling periods (Simón, 2008).

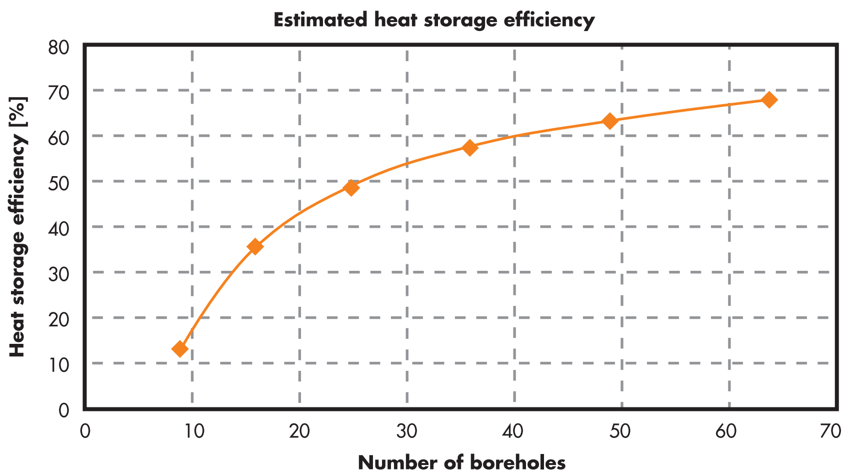

Figure 6.11: Estimated heat storage efficiency.

Competitiveness

It will be possible to use the highly exergy efficient GSHP systems also in the case of buildings with bigger heating and cooling demands. Solar energy can be stored in summer and can be used during the heating period, decreasing the annual consumption of the high exergy content energy carriers, e.g. fossil fuels. The vertical heat exchangers can be installed relatively close to each other and therefore less ground surface is needed.

Side effects

If the heat is extracted from the soil by an electrically driven heat pump then local pollution is avoided. In Central European climate conditions, the summer peak of solar energy gain can be utilised, but to run such a system significant solar collector area is needed, which increases the overall cost of the device. Another major cost is for creating vertical boreholes, which is currently very high.

Performance analysis tools

The available simulation programs are Simulink and FlowVent. These programs are not the most favourable for this typology of physical problems. Currently we are looking for the possibility to use more suitable tools.

Simulation studies

N/A

Demonstration projects

N/A

Monitoring results

Measured data from an ongoing project in Hungary of a ground source heat pump system are under evaluation. Energy is extracted from the soil by 19 vertical heat exchangers and a 64 m^2 soil collector. Temperature sensors are continuously measuring the soil temperature at different depths and distances from the heat exchangers. Based on these data the temperature field of the soil around the heat exchangers can be studied. Furthermore there are two heat storage tanks of 65 m^3 each one filled with water and covered by thermal insulation and dug under the ground. The system includes 20 m^2 solar collectors. Solar gains are used either to charge the seasonal heat storage tanks or to regenerate the soil around two selected vertical heat exchangers. In this way short and long term solar energy storage can be achieved and studied.

Planned further activities

This is the first running year of the heat pump in the experimental building. Therefore there are still no data available about the whole heating and cooling period.

So far only steady state calculations have been made to estimate the presumable performance of the above mentioned solution. Dynamic simulations are going to be made to get a clearer picture about the performance and usability of this conception.

Internet sites

N/A

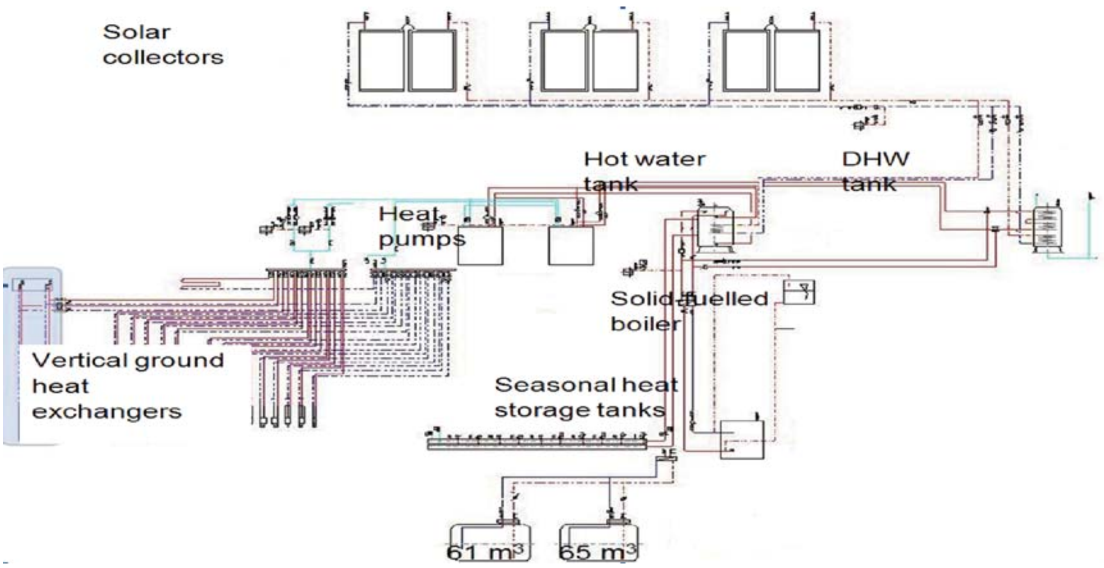

Figure 6.12: Plant scheme

6.5 Shallow ground heat storage with surface insulation

Main features of the concept
Coupling solar panels and a heat pump with a pipe system merged into the ground under the building, either warm or cool exergy can be stored and then released to the building itself (see Figure 6.13).

By covering large ground surface areas with insulation of sufficient thermal resistance the heat loss from the storage will be closer to the solution for a semi-infinite solid heated on the surface. Such storage will be favourable compared to a single borehole, especially when heat is supplied and extracted by the heat carrier in an annual cycle. The aim is to combine such an annual storage with solar collector and a low-exergy heating system in order to minimize the use of high quality energy for heating and/or cooling. The energy carrier can be as an example air in ducts or in a gravel bed or a fluid in pipes with high conductivity flanges.

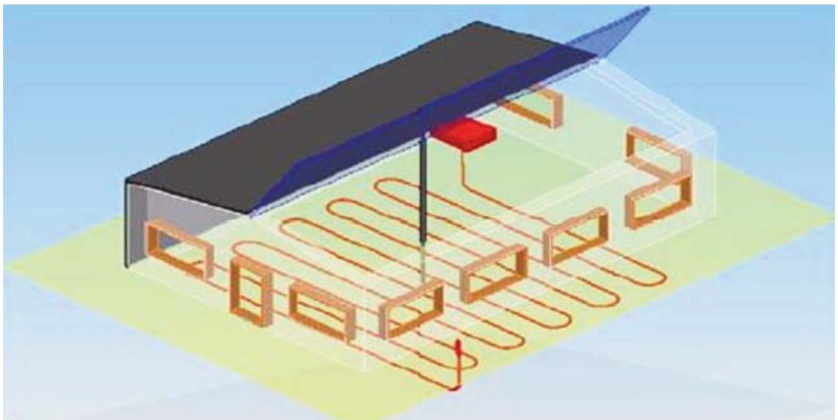

Figure 6.13: General view of the system.

Competitiveness
The cost for a 120 m borehole is in the order of magnitude of 10,000 €. The cost for 200 m^2 of 400 mm EPS insulation is in the order of magnitude of 4,000 € Under a new building some insulation is anyhow needed for the ground floor and such a thick insulation can also be used to provide forms for casting the ground plate in a most rational way. When the pipes are laid into the ground there is also the possibility to introduce elements for enhanced transversal heat flow from the pipes to the surrounding masses.

The possibility to store energy on an annual basis is also not realistic for a single borehole. However, in the case that energy is only extracted without any recharging, the borehole could be preferable.
Side effects
Positive side effects are the possibility of providing heating and cooling with a low exergy demand, the reduced heat loss to the ground and a lower risk for frost while on the other side special care will probably be needed for moisture from the ground.

Still to be accurately, the environmental feasibility, with particular concern to global climate, local climate, health and comfort, as well as the effects of the changed conditions for vegetation on top of insulation and the costs of the increased use of insulating material compared to normal foundation and a drilled borehole are evaluated.

Another important issue for this solution to take into account is the auxiliary power for the energy carrier.

Performance analysis tools
Applications for linear systems with constant flow and for non-linear systems where the magnitude and direction of the flow of the energy carrier can be varied with time have been developed in the FEM environment COMSOL Multiphysics.

Simulation studies
Studies have been carried out for a constant flow system and a system with variable flow of the energy carrier (Lazzarotto, 2008). Figure 6.14 shows results from simulations with airborne solar heaters connected to a 60 m air duct. After the duct, heat is extracted to provide a source for heating and DHW in a single family house. The flow has been varied in time and recirculated in the duct when feasible. The minimum outlet from the duct is 15-20 °C in winter.

Planned further activities
A two year project for field testing has been granted to KTH Building Technology (Sweden) and in another project the plan is to use such storage to provide low-exergy heating to cultural buildings where additional insulation or other refurbishment measures are not an option.

Present evaluation statement (2008-09)
Simulations of a ground storage coupled to a solar collector system and a house heating system has indicated that the storage temperatures can be kept above 20 °C in the coldest month (Jóhannesson, Lazzarotto, 2008; Lazzarotto, 2008; Noguera, 2007), even in Nordic climates (Stockholm). The system could provide direct heating for a large part of the year and then be combined with a heat pump working under favourable conditions for supplying heating for the coldest month and the additional heat for the domestic hot water.

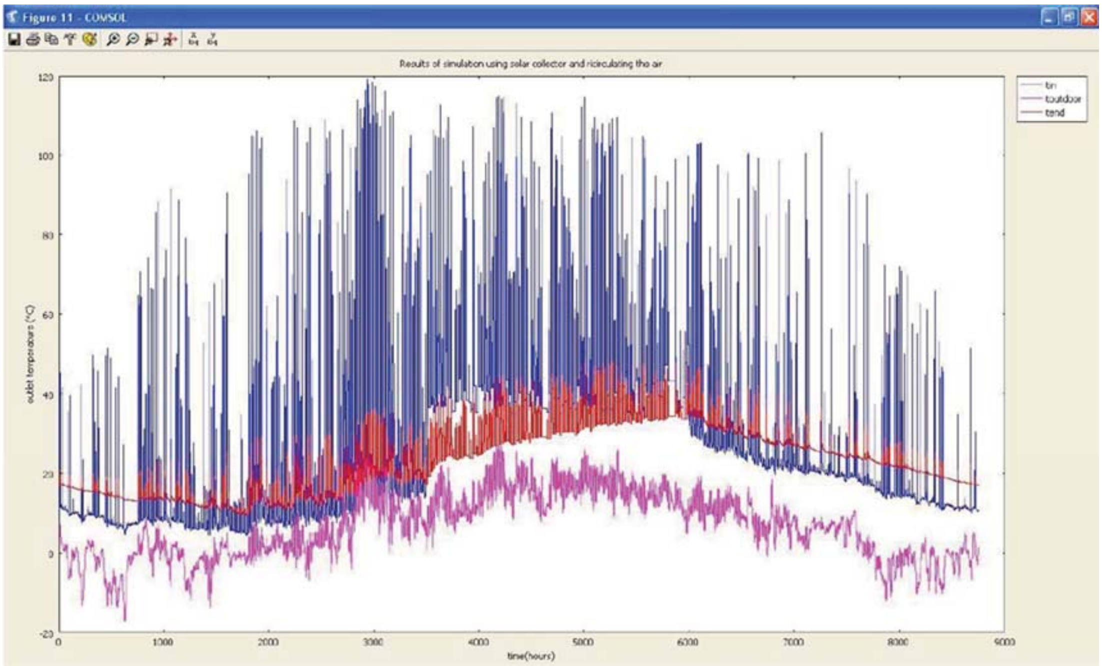

Figure 6.14: Temperatures in a yearly simulation. The purple line shows the outdoor air temperature. The blue and red lines display respectively the temperature of the air flowing in and out from the ground storage system.

6.6 Exergy recovery from wastewater in small scale integrated systems

Main features of the concept

In order to create a truly low exergy building the sources of unnecessary exergy consumption must be eliminated. These include the exergy consumed by warm air being released to the external environment, as well as the warm water. Recovery systems for exhaust air are already common, but wastewater is overlooked. Most well insulated high performance buildings now have nearly half of their heat demand coming from hot water production. In the described system a recovery system is being analysed to maximize the potential of warm wastewater to augment the performance of a heat pump. The heat from showers and other hot water demands is captured at the highest possible temperature and used to reduce the temperature lift needed for the heat pump to produce hot water. Thereby a low lift compressor can be used in the production of both low temperature (LowEx) space heating as well as for hot water production that requires a higher production temperature, but now receives a higher source temperature. The concept is diagrammed below and the potential change in COP is demonstrated in the T-S diagram (see Figure 6.15). This diagram displays the absolute temperature [K] and the specific entropy [J/kgK] in the y-axis and x-axis respectively.

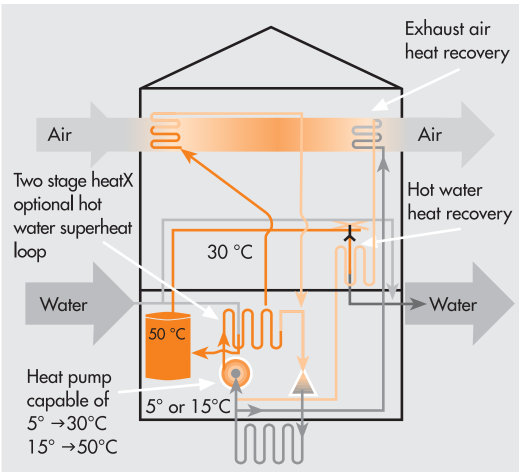

Figure 6.15: View of the system.

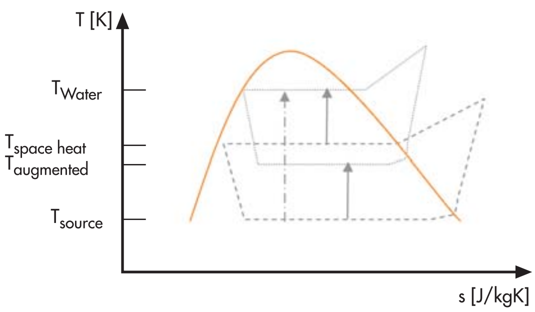

Figure 6.16: T-S diagram of the heat recovery process.

Competitiveness

A public-private partnership is under development through the Swiss Office for Innovation between the ETH Zurich (Switzerland) and Geberit AG. Geberit is the largest sanitary product manufacturer in Europe and will be able to bring the concept into fruition as an actual product that will be widely available through Geberit's extensive market share. The concept is also unique in that there are very few products for domestic wastewater heat recovery readily available at the scale being studied. The use of exergy also has the advantage of optimizing the system such that the maximum quality energy is recovered, providing the most benefit to an integrated heat pump system.

Side effects

As a part of the system design, new technologies are being implemented simultaneously at Geberit. This includes new flushing mechanisms for rapid operation of the system. Also systems to help very low flow flushing systems that have proper drainage are helped by the batch flushing process in this system, along with ideal integration with new greywater separation and efficiency improvements.

The heat exchanger used to extract heat also allows Geberit to expand into simple systems for heat recovery, such as those that simply preheat incoming water before it is heated in the hot water system instead of a complete integrated low exergy system. This allows for more simple retrofits to become an option as well.

This research is also being done in collaboration with the Technical University of Lucerne in Horw (Switzerland). There the creation of new low temperature lift heat pumps with innovative compressor technologies is being researched.

Proper protection will have to be maintained to avoid any possible cross contamination in the system. Also, bacterial build-up and fowling of the system could increase the likelihood of maintenance issues and will be important to consider in the initial design.

Performance analysis tools

The performance is evaluated using data for hot water usage over a year. A simulation tool has been developed at the University of Kassel (Germany) that can generate hot water usage data for a variety of uses. The inputs are taken from realistic statistical data for hot water usage to generate a random, but statistically accurate data set. This data set is input into a Matlab model of a heat exchange tank. The tank is optimized for different heat exchanger fluid flow rates and tank sizes and shapes in order to maximize the exergy captured.

Simulation studies

Initial results from the model for a hot water usage profile based on statistics from the USA for a four person home are shown in Figure 6.17. This shows the exergy extracted over the course of the year in solid line and the energy extracted in dotted line versus the flow rate through the heat exchanger (see Figure 6.17). When studying exergy, there is an optimal point at about 1.5 l/min, whereas energy analysis does not provide a clear optimum. This was also found to be true for the tank size, giving 400 l as optimal.

Demonstration projects

The first system will be built into the project at Bollystrasse 35 in Zurich. This project is managed by Prof. Dr. Hansjürg Leibundgut who leads the Building Systems group at the ETH Zurich where this research is being carried out. The project will contain other low exergy systems that are being researched and optimized in the group (Balini et al., 2007). The building, rendered in the Figure 6.18, will be a four flat apartment complex with an office on the first floor. It will be built over an existing old water storage tank from the city, providing an interesting 4 m high space to do further experiments on building systems. The project will begin construction in 2010 and be finished in 2011.

Monitoring results

The pilot project above will be actively monitored for performance of the system, as it will be one of the first implementations. This will include the monitoring of the borehole heat pump system, the low exergy heating, the decentralized ventilation and centralized exhaust recovery, as well as the wastewater heat recovery. This will also serve the purpose of giving Geberit data to finalize and upgrade their product specifications.

Figure 6.18: Rendering of the monitoring building.

Planned further activities

The implementation and evaluation in the Bollystrasse 35 building in Zurich will take place as stated above. The theoretical approach and analysis will be expanded and the model improved. The analysis will be evaluated in conjunction with Geberit to design a product or product line. The theoretical research have been presented at conferences in the fall of 2008 to gather input from experts and to discuss future work (Meggers, Baldini, 2008; Meggers, 2008; Meggers, 2008a). The final design and analysis will be submitted for publication in a relevant peer reviewed journal and used as a part of the PhD thesis of Forrest Meggers.

Internet sites

www.gt.arch.ethz.ch
www.viagialla.ch
www.geberit.com

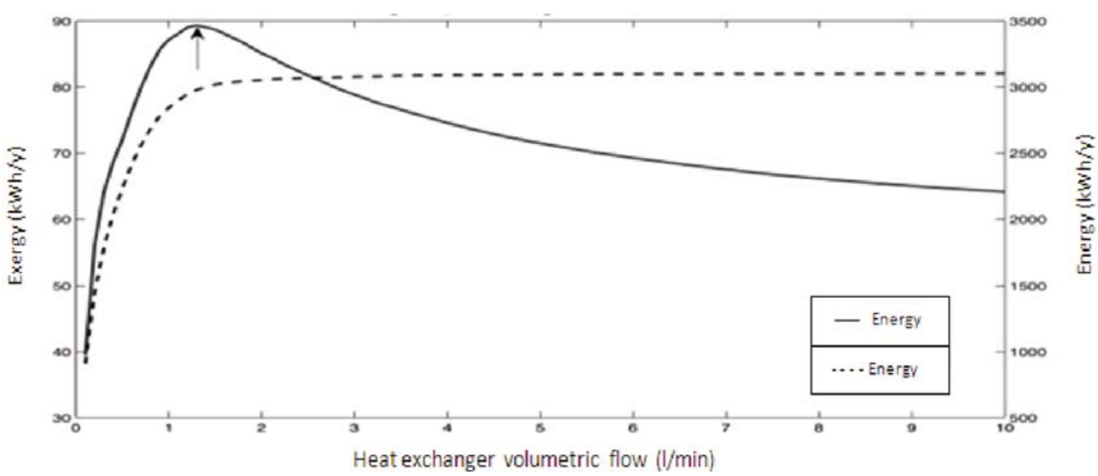

Figure 6.17: Exergy and energy flows.

6.7 Innovative configuration for cooling purposes: series design for chillers

Main features of the concept

Although a few companies supply chilled water at two temperatures, the industry standard design is to provide a single temperature chilled water supply. Water cooled chillers are normally configured with evaporators in parallel and condensers in parallel. The supply to return temperature differential for both evaporator and condenser water chiller flows is typically between 5.6°C and 6.7°C. The industry large scale chiller plants average approximately 0.267 system $kW_{electric}/kW_{cooling}$ at 24.2°C ambient temperature.

The improvement potential achievable with an innovative chiller design consisting on a series connection of several chillers is investigated here.

Figure 6.19 shows schematically the conventional design (left) and the innovative configuration proposed here (right). Temperature levels assumed for the performance of both designs are also shown in the diagram. Ideal exergy efficiencies for both configurations amount 8.33 and 12.14 respectively. This represents an improvement of 47%.

Demonstration projects

Such an innovative configuration has been checked for the cooling supply of a production plant in Malaysia (Solberg 2010).

In the innovative configuration chilled water is supplied at 7.2°C and 13.3°C with a common return with 11.1°C temperature differential. The design consists on eight centrifugal refrigeration compressors in series and has four condensers in series for a temperature differential of 8.3°C. The forecasted electrical energy demand for the chillers is then reduced from the conventional value of 0.267 system $kW_{electric}/kW_{cooling}$ to 0.135 $kW_{electric}/kW_{cooling}$ at 24.2°C ambient air temperature.

Increasing the chilled water temperature differential reduced the total flow of chilled water by 50%, meaning pipes, pumps, and valves were much smaller. A conventional design for the particular case of the investigated production plant required 27 pumps; the innovative design, in turn, required 9 pumps.

In the production facility studied the innovative configuration represents an improvement on the overall exergy efficiency of the production plant from 0.249 to 0.293.

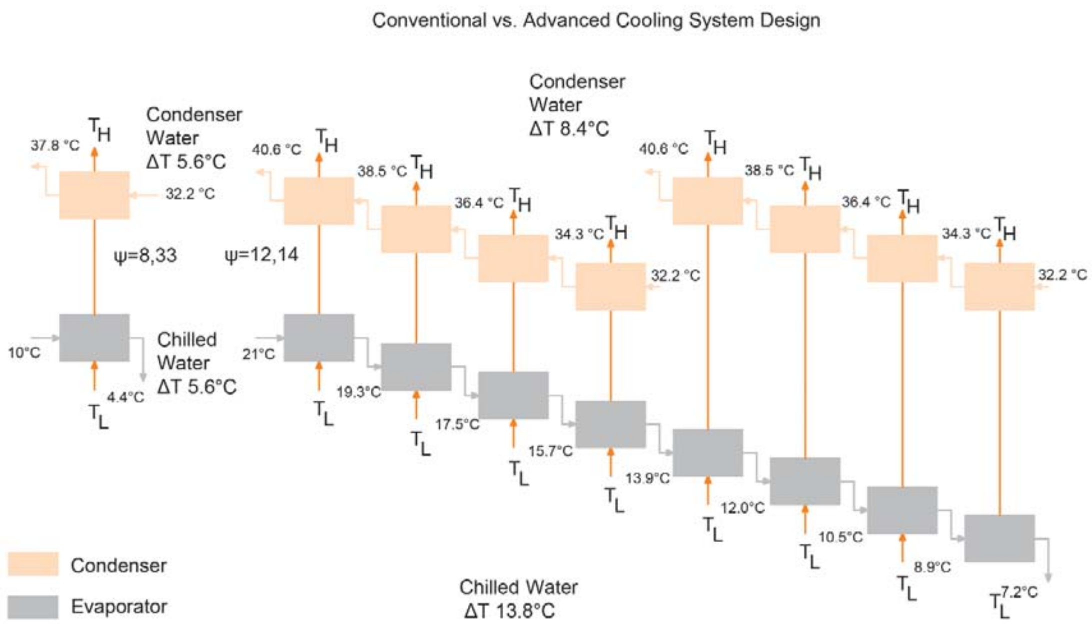

Figure 6.19: Conventional parallel configuration of chillers for cooling energy supply (left) and innovative series configuration for high efficiency cooling supply (right).

6.8 Conclusions

Buildings have rather low exergy demand compared to their energy demand, i.e. the exergy content of the energy demand is as stated above quite low. The desirable situation in buildings would be to have low exergy sources available, which are seldom encountered. Available energy sources are mostly of high quality and the mismatch between the quality of supply and demand results in unnecessary exergy destruction and low overall exergy efficiencies. Large exergy savings can be obtained by reducing the exergy demand in building and supplying it with a proper energy cascading, which can be cost efficient at a community level (see chapter 7). The previous case studies show that a decrease of the exergy consumption for heating and cooling processes in buildings is possible with current technologies, such as heat storage and heat recovery systems. Also, the use of cooling technologies such as evaporative and desiccant cooling has the potential to lower the use of electricity, which is energy with high exergy content, in buildings. The exergy optimization at building level is anyhow the first prerequisite to be obtained towards the exergy reduction at the community level.

The exergy optimization of a complex system such as a building is not a straightforward process. Several processes co-exist and need to be considered at the same time, making it a parallel rather than a serial process. As such, a decision that has a positive impact on one of the processes may have negative effects on other ones. Similarly, an improvement on a component can be counterbalanced by an unfavourable choice in another one. Therefore, a holistic analysis, considering all components and steps of energy supply in buildings is required.

However, as Figure 6.20 illustrates, exergy analysis shows optimization points that may not be found by a mere energy analysis. This is due to the possibility of considering the different forms of energy according to their thermodynamic value in the calculation of the exergy demand. The main purpose of exergy analysis in buildings is to show where the major exergy losses are located and to reduce them. The reduction of the exergy losses has a greater potential for so called energy savings. It is in fact possible to act on the energy demand, for instance by increasing the insulation of a building and reducing the required heat emission temperature, but also on the

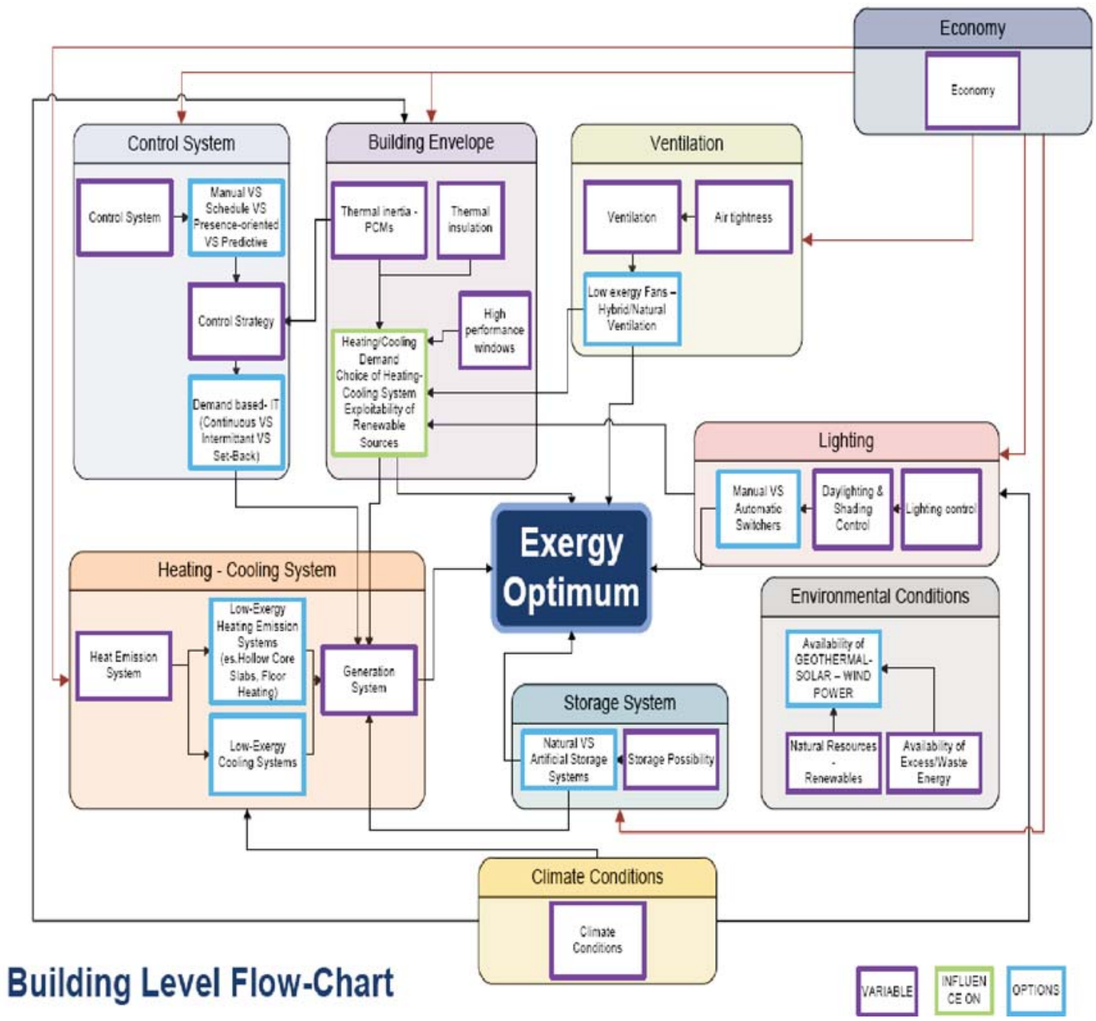

Figure 6.20: Flow chart of the main variables influencing the exergy optimum.

energy supply, by matching exergy supply and demand, which a mere energy analysis doesn't disclose.

To illustrate the effects and the connections of variables and parameters involved in the process of minimizing the exergy consumed in a building, some of the most important have been listed and connected in the Figure 6.20.

Heating & cooling

The exergy approach can reveal its potential to improve the energy use in buildings if all the related processes are considered. Usually, to reduce the use of energy very much attention is paid on generation systems. The replacement of a conventional boiler with a condensing boiler or a heat pump often gives clear improvements in the energy use, due to higher conversion efficiency.

The scheme in Figure 6.20 stresses the importance of the generation system in the building climatization process but it also underlines how the choice of a generation system should be dependent on the emission system. A floor heating/cooling wouldn't perform exergetically better than a radiator if coupled with a traditional boiler. Much better performance is expected from such a system working with a heat pump. Coupling the different systems must be done carefully taking into consideration the characteristic performance curves of every system.

Control strategy

The exergy performance of a climatisation system is deeply influenced by the control system and strategy. The opportunities given by the wireless networks, cheaper and more reliable than in the past, pave the way to a radical change in the way systems are controlled. Wireless sensors can measure parameters such as temperature and humidity and detect presence. As wireless sensors have long stamina, there is no need to have them connected to the plug and thus they are suitable for retrofitting of buildings. Energy wastes due to empty buildings heated because of scheduling strategy can be largely reduced.

Moreover, a predictive control strategy could further improve the energy use in buildings. Data gathered from indoor and outdoor sensors can be merged with the characteristic parameters of the building envelope (such as response factor) and of the heating system (efficiency vs. load factor for boilers or COP vs. temperature for heat pumps) to have them working in the highest performance conditions to comply with the desired effect (i.e. the comfort conditions in the expected time when the room is occupied). The more integrated the control system to the heating/cooling system and the building envelope is, the more efficient the energy management results.

Building shell/envelope

The characteristics of the building shell have undoubtedly a strong influence on the exergy demand and consumption of the building itself. Parameters such as insulation, thermal mass and window performance, whose choice is determined by the climate conditions (temperature distribution over the year, distribution and intensity of solar radiation – both as heat gains and daylight), firstly determine the response of the building to the external varying conditions. A smart choice of the thermal mass can let the temperature oscillate within the comfort range, especially in temperate mid-seasons when the temperature varies closely to the comfort limits therefore cutting down the energy for heating and cooling (see Figure 6.21).

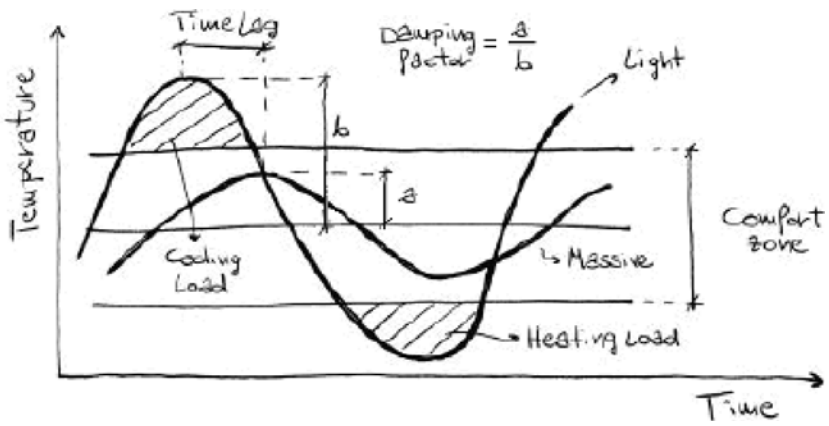

Figure 6.21: Daily building heating and cooling load for a massive and a lightweight construction building (Rinaldi 2009).

Thermally activated building components such as hollow core systems give the advantage of increasing the depth at which the energy is stored, that is equivalent to say that a larger quantity of mass stores energy. This has positive effects on the thermal stability of the building but needs to be accurately accounted for when dealing with the control strategy.

The charge/discharge of the thermal mass can be then done by means of mechanical ventilation, instead of active heat generation components. This increases the use of electricity consumed for heat circulation but on the other side exergy for heat conversion is saved. Which is the most profitable choice depends, among the other factors, on the temperature profile, the type and use of the building, the heat vector and the active components.

Storage and environmental conditions

Storage systems can influence directly and indirectly the exergy consumption in the building. The possibility to store energy can reduce the exergy directly destroyed in the generation system by partially replacing the exergy supplied or by increasing the performance of active systems such as the generation system. As an example, we may consider the cooling demand met by using directly the cooling energy accumulated during the cold season or using this storage system as a sink for improving the COP of a chiller (see Figure 6.20).

The most limiting feature of the renewable sources is their availability in time while exergy and energy demand in buildings have a more defined trend. Those energy sources, such as solar power, are scarce in winter time at higher latitudes (like in Scandinavian countries) when they would be very much needed to cover the heating demand. Still, throughout the year there is enough radiation to virtually cover the energy demand of buildings. A seasonal storage unit would make it possible to put to use renewable sources or waste energy from other processes that may be available.

Economy

All those technical considerations have to face the main decision driver, which is the economical feasibility, which in Figure 6.20 is graphically connected to all technical fields, as it has a fall-out effect on all of them. The challenge is to apply the most cost-effective solutions and to make them market-appealing.

Also, it has to be kept in mind that due to the long term life span of buildings an investment which nowadays has insufficient competitiveness can be financially rewarding in a close future due to the quickly changing prices of energy.

As a final remark, some conclusions can be drawn from this chapter:

- There is not a unique way to design or optimize a building: waste heat, renewable energies and storage systems are to be used together and linked.
- Exergy approach is a powerful tool to analyse and optimise but solutions are to be found according to the local conditions, sources availability and technical and economical feasibility.
- Technical feasibility is an essential point in decision making. What can currently be seen as a state of the art solution (solar panel for heating) can in future be much less appealing or competitive due to the improvements of collecting technologies that may allow the exploitation of the sources closer to the theoretical maximum.
- The definition of a reference state and the theoretical maximum values, though making the analyses more complex, has the advantage of giving a more accurate description of the variables and phenomena.

[32]This case study has kindly been submitted to the ECBCS Annex 49 working group by Xiaoyun Xie and Yi Jiang from Tsinghua University (China) as guest participants.

[33]This case study has been kindly submitted to the ECBCS Annex 49 working group by Xiaoyun Xie, from Tsinghua University (China) as guest participant.

[34]This case study was kindly submitted to the ECBCS Annex 49 working group by Tamás Simon from the Budapest University of Technology and Economics, Budapest (Hungary) as guest participant.

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7. APPLICATION OF THE EXERGY APPROACH TO COMMUNITY CASE STUDIES

Managing energy supply and costs within a community requires that community to have a vision for its future development. Plans and strategies for developing energy supply structures for communities would incorporate the development of programs and projects that create resilience within the community and thereby a resistance to the impact of energy market fluctuations.

In this chapter several community case studies which have decided to go through such a planning process and implemented development projects to modify their energy supply structures are presented. Table 7.1 shows an overview of the community case studies included in this chapter. Besides a general description of the community and the innovative supply systems used, the relevance of the deployed technologies as "LowEx" systems is explicitly stated for each case.

Prior to the case studies a general introduction on the community scale is given. Here, the concept of community as used in this report is introduced, followed by some words on the operation and development of community supply structures.

The Community

Interestingly the term "community" is commonly used with apparent disregard for a consensus on its meaning. Here, the term community refers to a predetermined study area over which the decision-makers have authority or influence. For a City Hall this may be an entire municipality, although the evaluation of an entire city might be complex or unwieldy: it could also be a more modest development such as a downtown rejuvenation project. To enable categorisation of demands the study area should be heterogeneous in its design and contain a mixture of building types with a variety of energy uses and demand profiles. Such mixtures could include such properties as residential, commercial, retail, institutional, and even industrial uses.

Figure 7.1 shows a scheme for the energy and exergy supply and interactions of a community system (Solberg, 2010). The dashed line represents the boundary enclosing the community, characterized as energy system. Respectively, energy and exergy inputs and outputs can be found in the diagram.

The planning and decision making process

Figure 7.2 suggests that change in energy use patterns within a community may be initiated at a variety of levels. At each level the decision-makers are different. The simplest change is often at the level of the end-user. For example a manufacturer might improve the efficiency their refrigerators, his cars or light bulbs. Each end-user would purchase this new product based upon anticipated cost savings, but for significant savings to be made, the number of end-users purchasing this new product must be large.

On the other hand, a change in energy type at the system level would involve fewer stakeholders and theoretically should be easier to initiate, but it would require increased investment. For example, a simple cycle plant might decide to recover its waste heat and employ this within a district energy system, displacing oil heating in community buildings. At the community level, this change would likely be the expensive but also environmentally the most far reaching of the alternatives. It is at this level of change towards which the community case studies presented in this chapter are oriented to.

Table 7.1: Summary of community case studies.

community	country	LowEx highlights
Alderney Gate	Canada	Sea water cooling coupled with borehole thermal energy storage
Andermatt	Switzerland	geothermal energy systems
Heerlen	Netherlands	low temperature emission systems, low temperature district heat from old coal mines
Letten	Switzerland	geothermal energy systems
Minnesota	USA	co-generation and district heating
Oberzwehren	Germany	utilisation of waste heat from CHP as low exergy supply source
Okotoks	Canada	solar thermal heating systems coupled with seasonal ground thermal energy storage
Parma	Italy	Low temperature heating systems coupled with efficient ventilation systems
Ullerød	Denmark	low energy district heating, ground source heat pump (GSHP) and air-to-water heat pump (AWHP).

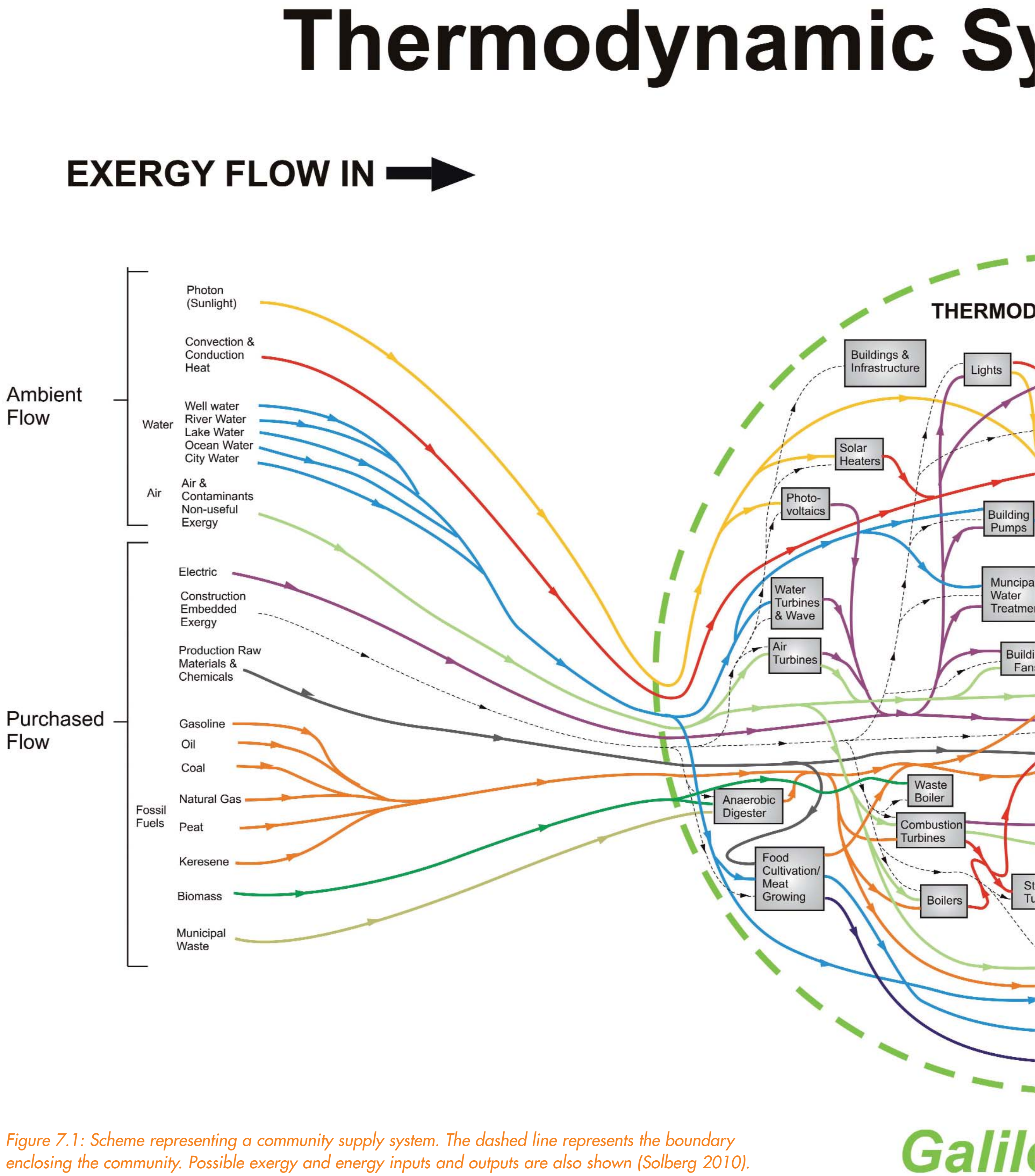
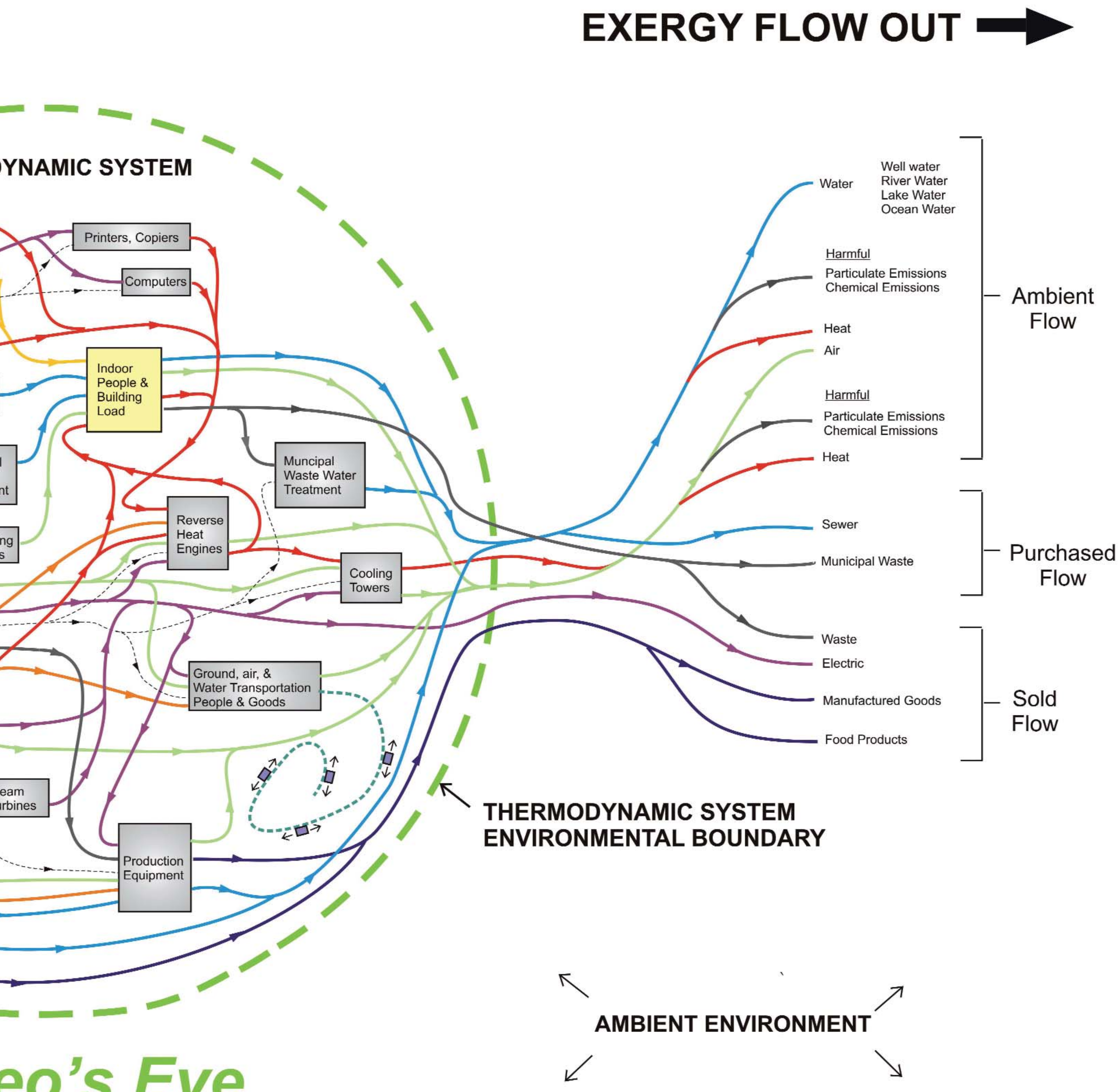


Figure 7.1: Scheme representing a community supply system. The dashed line represents the boundary enclosing the community. Possible exergy and energy inputs and outputs are also shown (Solberg 2010).

ystem Exergy Flow



eo's Eye

As already stated in this report, exergy is a comprehensive measure of the potential for an energy supply to do work (Shukuya, Hammache, 2002) and therefore offers the ability for users to manage the quality of energy. By knowing the characteristics of the task to be undertaken (demand), one can select the most appropriate energy stream for it (supply). Energy sources within the community must be separated and categorised according to their quality (i.e. exergy content) before being aggregated to form specific energy supply groups. Similarly, categories for energy demand types can be defined. This is done graphically by means of the "arrow" and "PRE-exergy efficiency" diagrams shown for each case studie presented in his chapter.

With an understanding of the capacity and capability of each category, supply and demand integration would follow, linking energy supplies and demands in the most effective manner and where possible, using local resources to generate that energy.

Often it is also possible to align tasks in such a manner that the output energy stream from one task becomes the input energy stream for another, thereby cascading through the activities and maximising the effectiveness of the supply. This line of thinking is similar in some respects to Pinch Technology (Wall and Gong, 1996) as used within an industrial process where the cooling and heating requirements are coordinated to minimise the need for external energy. However, the fundamental difference between the use of exergy and energy in Pinch Technology is that for energy a satisfactory solution is obtained when supply and demand are balanced or their difference is minimised. For a satisfactory exergy solution supply and demand not only have to be balanced, as before, but the exergy level at the final step has to close to that of the ambient temperature – a much more demanding condition.

Diagrams for characterising community exergy performance

The characterisation of the exergy performance of different case studies and community concepts is presented here by means of diagrams that enable visualization of the performance of a given case study and make different community energy supply concepts comparable. They are included under the section "LowEx Diagrams" in the respective case study. Arrow diagrams (see section 5.3.1) and PER-Exergy efficiency diagrams (see section 5.3.2) introduced in chapter 5 are used here to characterise graphically the exergy and energy performance of community supply systems.

There are some projects which have already been implemented. Therefore monitoring results are available and the contribution of different energy sources and technologies used to supply them is known. In this cases the PER and exergy efficiency figures are shown for the mix of the different energy sources used in the supply. Examples of this situation are the Okotoks Drake Landing Solar Community and Alderney Gate projects. Some other projects are still in planning or under development. Here, different options regarded for energy supply are characterised separately. An example of this situation is the City of Parma.

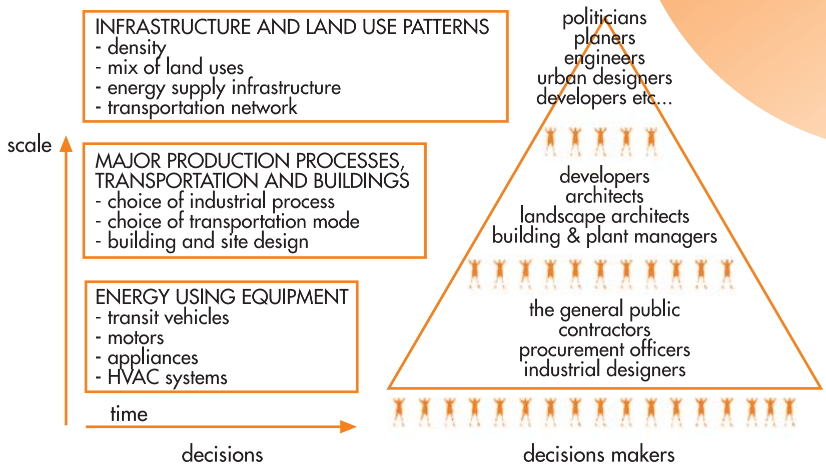


Figure 7.2: Advanced coaxial energy storage: heat exchanger design.

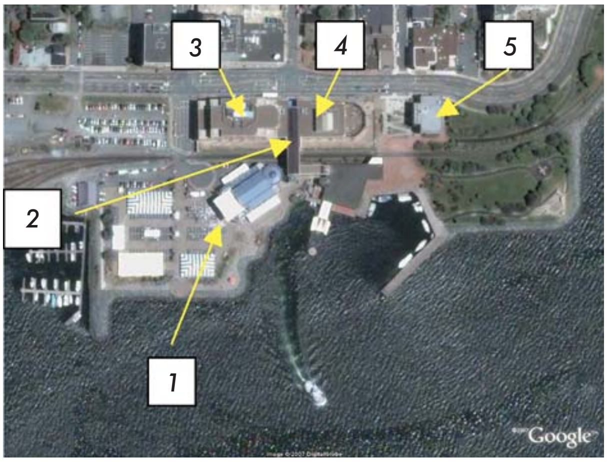
7.1 Alderney Gate (CA)

7.1.1. General description

This low-exergy project integrates demand side management within the Alderney Gate Complex in Dartmouth, Nova Scotia, with a renewable energy cooling supply (seawater) and in-ground seasonal thermal storage to eliminate the use of electrically driven chilling equipment.

The overall project objective is to develop a cooling system for a municipal building complex that employs the cooling effect of sea-water either directly to the building's cooling system or indirectly through a Borehole Thermal Energy Storage (BTES) system.

The project demonstrates a systems approach to building energy management It successfully demonstrates the use of borehole thermal energy storage for cooling purposes for the first time in Canada.



1) Alderney Landing
2) Alderney Gate
3) Dartmouth
4) Dartmouth Ferry Terminal
5) School Board

Figure 7.3: Alderney gate complex (Canada)

7.1.2. Methodological description

Water is drawn from the harbour adjacent to the project site and passed through a heat exchanger before being returned to the harbour. The extracted cold is then passed directly to the building's own cooling distribution system or, during periods of low cooling loads, passed through a series of vertical borehole heat exchangers and stored in the ground.

7.1.3. Technical description

The in-ground cold storage system consists of a field of 80 boreholes that will incorporate in each borehole, a coaxial heat exchanger of a design new to Canada (see Figure 7.5). The technology is called the Advanced Coaxial Energy Storage (ACES™) borehole and is calculated to reduce both the number and depth of boreholes required. Water, cooled by the seawater, is passed through the heat exchangers during the winter months to create a store of cold that may be called upon and discharged when needed (see Figure 7.4). The technology will be installed in a car park site adjacent to the Alderney 5 Complex.

A peak seawater flow of 181 m^3/h is drawn through 250 mm piping from a point 10 meters into the harbour and 3 meters below the low water mark, passed through a titanium heat exchanger and returned 3 meters into the harbour and 50 meters south of its intake. The shore-mounted titanium heat exchanger increases the seawater temperature by a maximum of 6°C.

Heat exchanger, pumps and other control devices are housed in a new building to be located on the adjacent car park. The building cooling system will circulate fresh water, cooled by the titanium heat exchanger. When the seawater is cold enough,

Table 7.2: General project and system data for Alderney case study.

GENERAL PROJECT DATA		GENERAL SYSTEM DATA	
Municipality	Halifax Regional Municipality	Building number	5
Constructor	High Performance Energy Systems	Cooled Area	30,741 m^2
		Cooling load	1,758.5 kW
Installer	High Performance Energy Systems	Maximum Seawater Supply Temperature	8°C
District Energy	High Performance Energy Systems	Maximum Seawater Return	14°C
		Temperature	
Design Team	High Performance Energy	Annual cooling load	2,500 MWh (thermal)
		Storage volume	864,000 m^3
Environment	Canada	Borehole Storage Thermal capacity	500 MWh (thermal)
Hand-over	2008	Borehole COP	16:1:0

freshwater passes directly to the building distribution network and the installed fan-coil units. Excess chilling is stored by cooling the earth around the borehole storage area. When the seawater temperature is too high for direct cooling, the fresh water is passed through the chilled borehole storage field before being passed to the building distribution network.

The coaxial heat exchanger improves thermal and exergetic efficiency by cutting the ΔT (fluid-ground) to 1-2°C; giving the fluid direct access to the borehole wall and by providing a very low pumping resistance. The design results in a smaller storage volume for the same cooling load and eliminates the use of mechanical chillers.

A custom designed control system optimises the system components, the storage temperature distribution and the activities within the Alderney 5 Complex.

7.1.4. LowEx Highlights and Diagrams

7.1.4.1. LowEx Highlights

In the project sea water cooling coupled with borehole thermal energy storage is planned to be used for cooling purposes. Both thermal energy ground storage as well as the cooling potential from the sea water have low temperature levels and are therefore suitable LowEx sources for supplying cooling demands.

7.1.4.2. LowEx Diagrams

Figure 7.6 shows the Primary Energy Ratio and Exergy efficiency for the energy mix regarded in the Alderney Gate complex.

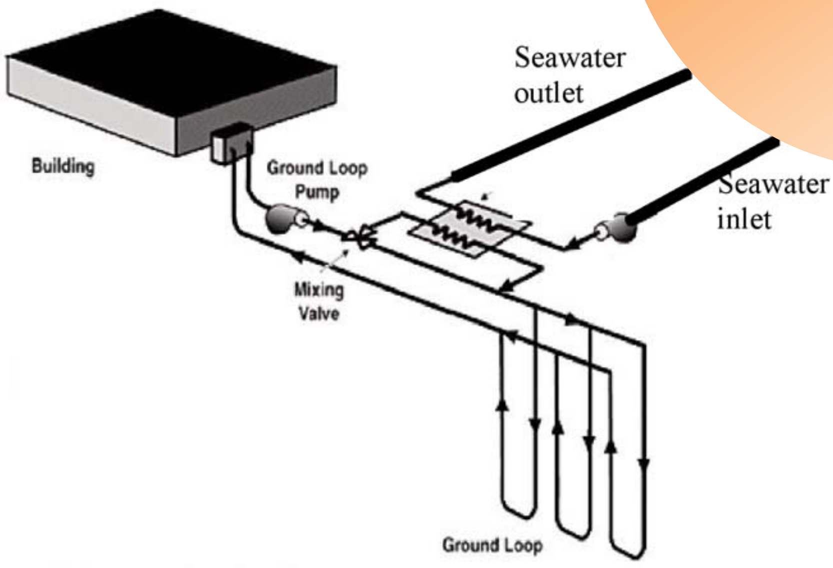


Figure 7.4: Simple scheme showing the connection of the building with the seawater cooling loop and borehole heat storage.

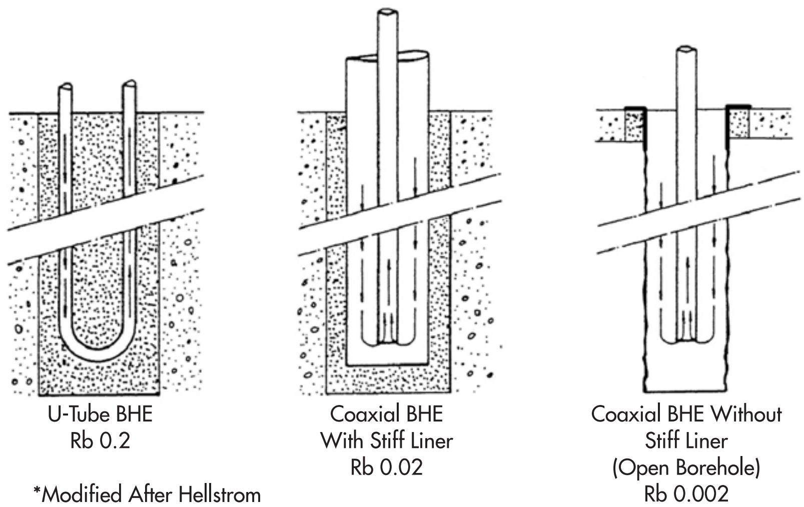


Figure 7.5: Advanced coaxial energy storage: heat exchanger design..

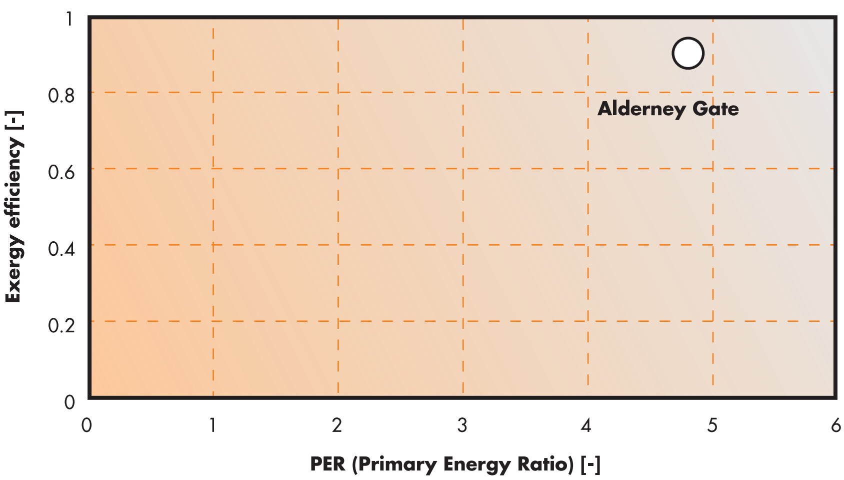


Figure 7.6: PER ratio vs exergy efficiency diagram for the energy supply mix in the Alderney Gate complex.

7.2. Andermatt (CH)

7.2.1. General description

Andermatt is an alpine region of Switzerland where an entirely new tourism resort is being built. The cold climate implies a high heating demand with a low cooling demand. One goal of the project is for the energy use at the resort to be CO_2-free.

The energy concept for this resort in the Swiss Alps considers the high potential of deep geothermal energy from mountain tunnels. The temperature level of the heat reservoir is not high enough to supply building energy demands directly. Instead, the concept is to use this low temperature reservoir to minimize temperature gradients in energy supply systems, thereby minimizing exergy destruction. By incorporating new heat pump technologies, much higher COP's can also be achieved. The viability of the projects depends on the evaluation of the value gained versus the extra infrastructure or transport required for implementation. These aspects are still under evaluation in ongoing research.

This case study demonstrates the transport of and utilization of heat at what would be absolutely low temperatures (i.e. being low exergy sources available locally), but compared to other ambient sources have relatively high exergetic potential and minimal environmental impact.

7.2.2. Methodological description

The energy masterplan includes a low temperature loop around the resort with decentralized heat pumps. The loop is fed by a seasonal geothermal storage field of borehole ground heat exchangers of 300m length, with a temperature of 0-5°C. The other source is the Furka tunnel, which has an entrance located 6 km away (see Figure 7.7). It supplies a constant flow of drainage water at 13°C, which can be piped to the resort.

The tunnel water is of special interest in the mountains. Because of the low ambient temperature, the exergetic value of this relatively low temperature source is actually quite high.

This project is ongoing and research includes the feasibility of the low temperature hydronic network supplying the heat pumps. Also of interest is the interplay between the two reservoirs and the relationship between the exergetic value of reservoirs versus the transport cost from the tunnel.

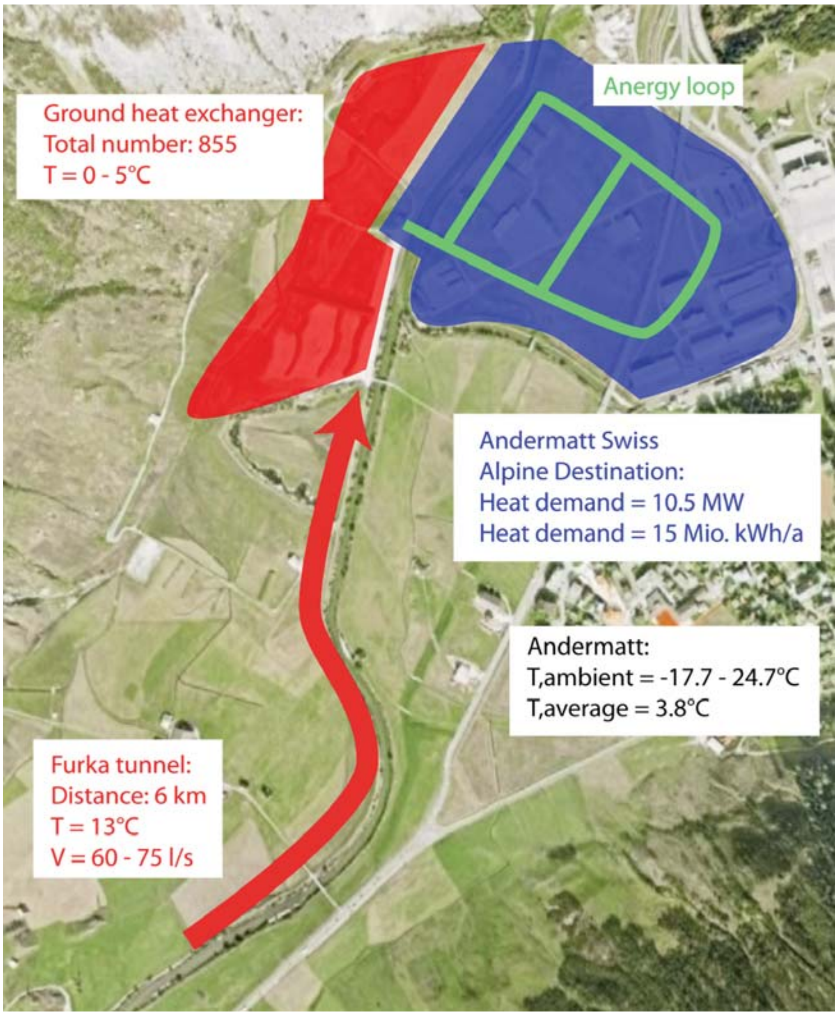


Figure 7.7: Energy plan for the new Andermatt Alpine Resort, at 1447 m altitude.

7.3. Heerlen (NL)

7.3.1. General description

This low-exergy project uses warm and cold water volumes from abandoned mines. In the Mine Water Project in Heerlen water from abandoned and flooded mines is used as a new sustainable energy supply for heating and cooling of buildings. The temperatures that have been found (16..30°C) are used in very well insulated buildings, with energy efficient ventilation systems and low temperature emission systems, the thermal comfort is excellent during 365 days/year. At the same time there will be a CO_2 reduction of 50% in comparison with a traditional solution.

The project started in February 2006 in Heerlerheide by drilling the warm wells. In October 2007 the last well was drilled, the cold well.

This project is situated on the concession of the ON III pit in a relatively deep mined area with warm water wells (30..35°C). The area of buildings included in the project are:

- 33,000 m² dwellings (single family dwellings and residential buildings)
- 3,800 m² commercial building
- 2,500 m² public and cultural buildings
- 11,500 m² health care buildings
- 2,200 m² educational buildings

The first new building and construction activities in Heerlerheide Centre have started in 2006. the total plan will be realised between 2006 and 2011. All planned buildings will be connected to the energy supply (heating and cooling) from minewater. All these buildings are planned in a very compact area, which is very favourable for energy distribution. The building location is situated between two warm wells. Next to it, the planned building functions require heating as well as cooling. The energy supply includes the building of an energy station and a small scale distribution grid from this to the buildings. In the energy station the minewater is brought to the necessary heating and cooling levels by heat pumps. In order to facilitate the process and to guarantee all real estate developers, involved in this building plan, the delivery of energy to the building the main investor, is realising the exploitation of the energy supply, including the building and construction of the energy station and distribution grid. It is important to realise, that with minor modifications this energy supply can also be functional and operational without the application of minewater.

Figure 7.8 shows the primary grid connection between the wells and building locations.

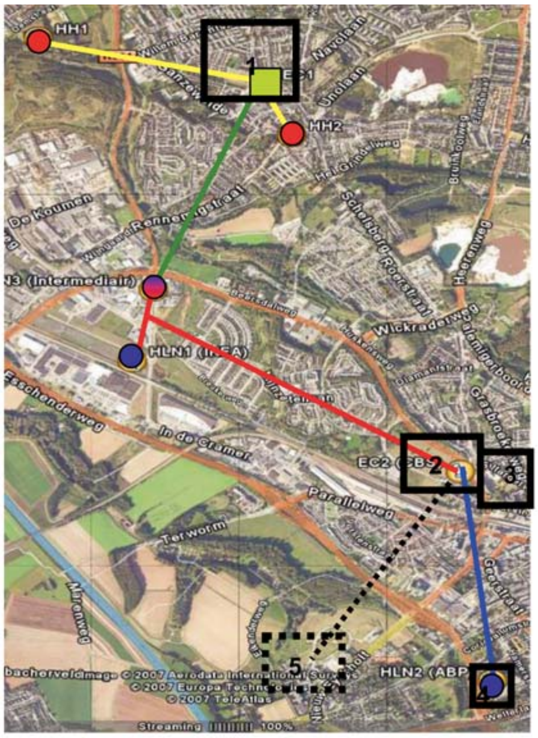


Figure 7.8: The city of Heerlen with the position of the warm and cold wells, as well as the building sites to be supplied.

- Warm well
- Cold well

1. Heerlerheide Centre
2. CBS offices old and new
3. Maankwartier
4. APG building
5. (Campus (Arcus, HS Zuyd, OU))

7.3.2. Technical description

Minewater is extracted in this project from four different wells with different temperature levels. The primary energy grid transports the extracted minewater from the warm wells (~30°C) to local energy stations. In these energy stations heat exchange takes place to the secondary energy grid (from the energy station to the buildings). This secondary energy grid provides low temperature heating (35..45°C) and high temperature cooling (16..18°C) supply and one combined return (20..25°C) to an intermediate well. The different temperature levels of the wells considered can be seen schematically in Figure 7.9.

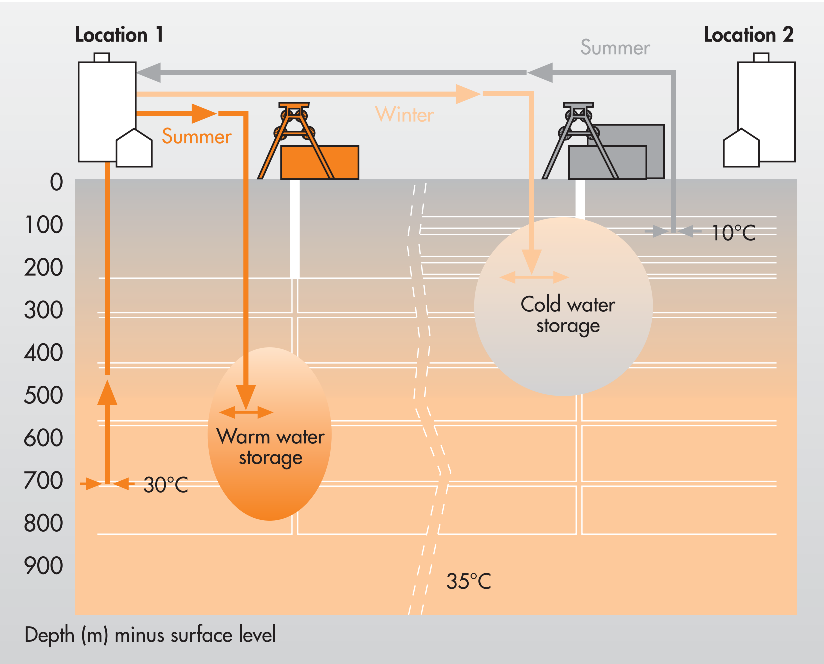


Figure 7.9: Minewater energy concept: depth and temperature level of the wells in the project.

The warm wells (~30°C) are found on a depth of 800m. On a level of 400 m mining took also place. Here are the relatively cold wells situated. The combined return water (20..25°C) is transported to an intermediate well at a level of 450m. The well locations and energy stations are connected by three pipelines of 7 km each.

The temperature levels of the heating and cooling supply are guaranteed in the local energy stations by a polygeneration concept existing of electric heat pumps in combination with gas fired high-efficiency boilers (see Figure 7.10). The surplus of heat in buildings which cannot used directly in the local energy station can be lead back to the minewater volumes of storage. DHW is prepared in local sub-energy stations in the buildings by heat pumps, small scale CHP or condensing gas boiler, depending on type of building and specific energy profile. The total system will be controlled by an intelligent energy management system including telemetering of the energy uses/flows at the end-users.

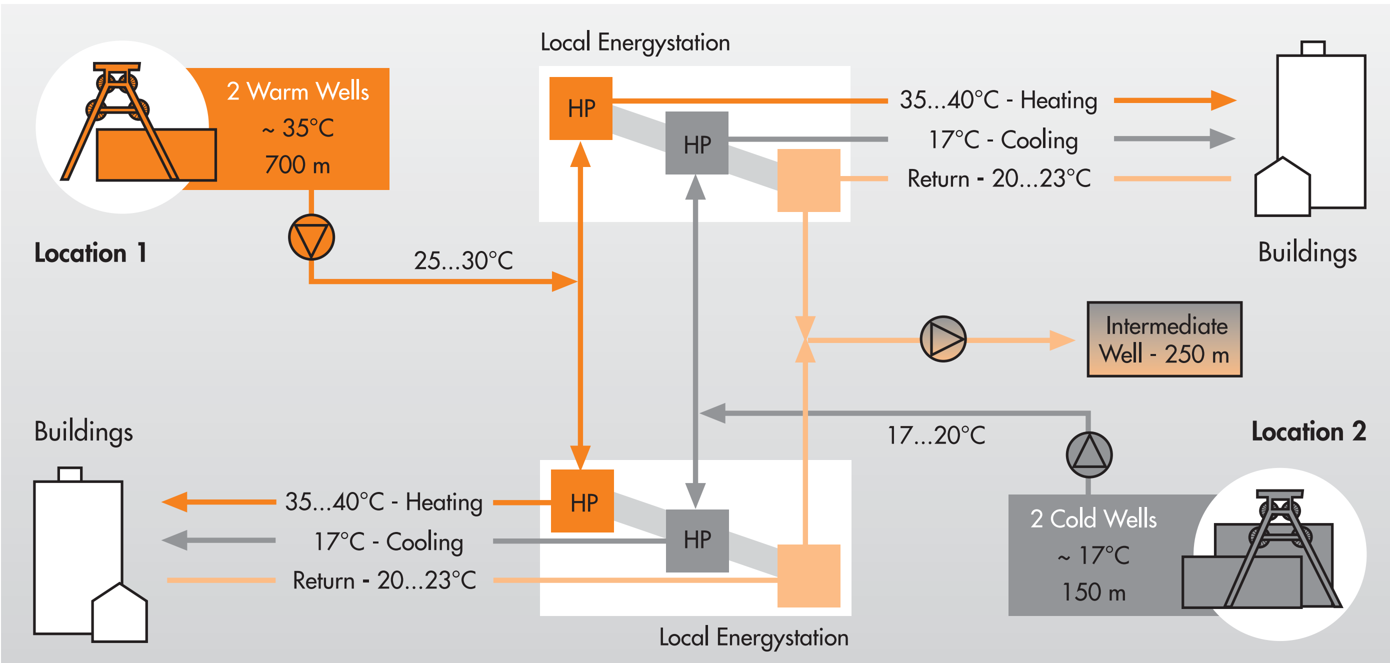


Figure 7.10: Energy management system: temperature levels and lifts in the different parts of the energy supply concept planned in Heerlen.

7.3.3. LowEx Diagrams

Figure 7.11 shows the Primary Energy Ratio and Exergy efficiency for the minewater-based supply technologies considered in the community of Heerlen (NL).

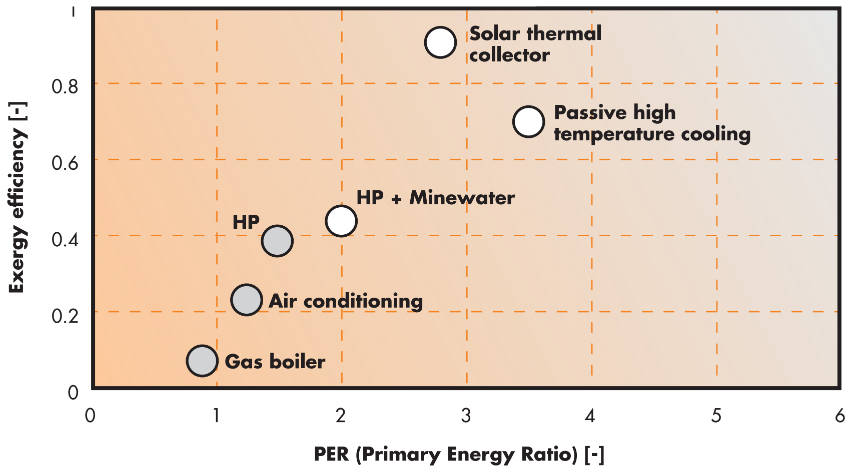


Figure 7.11: PER ratio vs Exergy efficiency diagram for the energy supply options chosen in Heerlen (represented by the white dots). For comparison, grey dots represent the performance of conventional technologies.

7.4. Letten Zürich (CH)

7.4.1. General description

This case study deals with one energy concept being studied for the supply of the ETH Zurich central campus. One goal of the Energy Strategy to be implemented is to halve the CO_2-emissions of its structures and buildings by 2020. The energy supply concept focuses on the potential exploitation of the temperature differences between a stratified lake and the mixed river at the lake output. Similarly as case study 7.2, the temperatures and temperature differences are not enough for a direct supply of the required energy demands. Again, the idea is to promote and use this low temperature (low exergy) sources available to reduce the temperature differences in common building supply systems, thereby reducing exergy consumption in such systems.

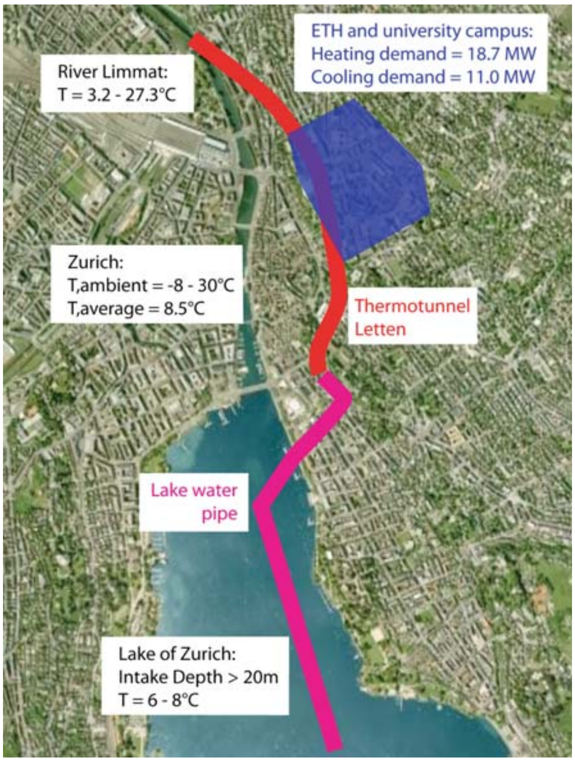


Figure 7.12: Thermotunnel Letten for the potential energy plan of the ETH Zurich.

7.4.2. Methodological description

The concept considers reopening an old train tunnel that has been filled in using microtunneling. This tunnel passes underneath the campus. This "Thermotunnel" (see Figure 7.11) would then connect a downstream part of the Limmat river directly with its tributary, the Lake of Zurich. The temperature difference between the two would create an exergy potential at low temperature. Compared to thermal networks with only one reservoir, this system makes use of the temperature differences between the two reservoirs. Due to potential environmental disturbance these sources are not allowed to have their temperatures disturbed. Campus heating and cooling systems from one source would cause a considerable disturbance. Instead of disturbing one source, the tunnel can be used to extract or deposit heat between the two tanks to the temperature gradient between the fully mixed river current and the stratified layers in the lake.

7.4.3. Technical description

The energy from the water can be used for direct cooling and for heating with a central heat pump. With typical extraction temperatures of around 6°C combined with low temperature emission systems on the buildings of the campus, high COP systems are expected to minimize the renewable electricity that must be supplied.

7.4.4 LowEx Diagrams

A graphical representation of the quality levels of the energy supply and end-use categories considered in this case study is shown in the arrow diagram in Figure 7.13.

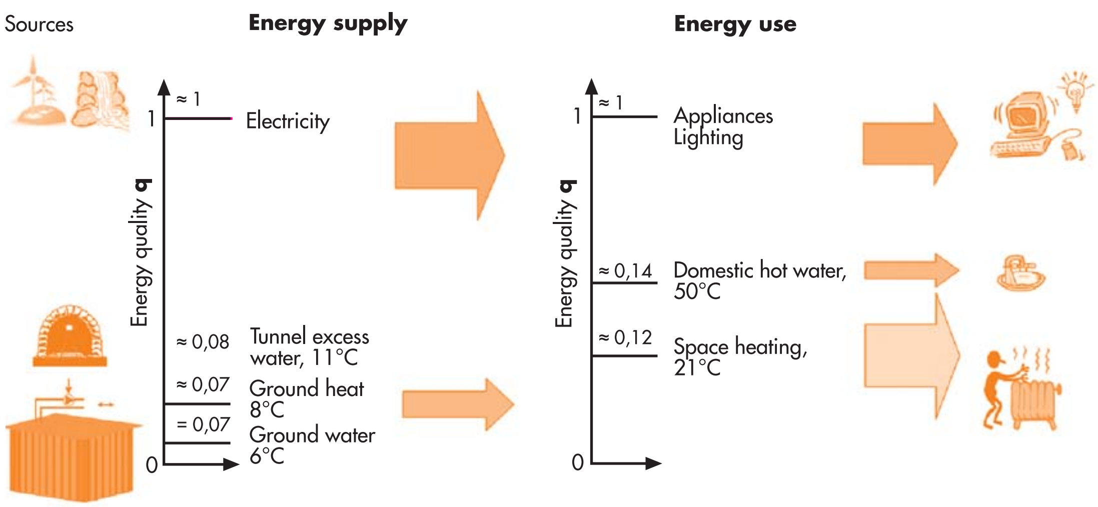


Figure 7.13: Matching of the quality levels of energy demand and supply for the Thermotunnel Letten case study. The different energy supply options regarded as possible supplies are characterised separately.

7.5. Oberzwehren (GER)

7.5.1. General description

The city of Kassel, situated in the centre of Germany, is aiming at carrying out an environmentally ambitious housing project within the coming years. The building site is situated on the estate of the former School for Horticulture of the University of Kassel in the city district of Oberzwehren. It is bordered by access roads and private estates. To the north, a mixed-use area borders the site. To the north-west, there is a university campus, to the west, multi-family buildings, and to the south-west and east, single-family houses can be found. Floodplains from a small river can be found to the south. Bus and tram connections to the city centre exist.

On the agricultural sample area of the site, an ecological nursery was established in 2006. This is to remain. The new buildings will be developed in two separate areas, for which different urban and energetic solutions will be developed. The buildings are to comply with high ecological standards to sensibilize citizens for environmentally-friendly living in the city of Kassel.

A district heating return pipe from the local utility company circulates close to the residential area. It is planned to use this return pipe to supply domestic hot water and space heating demands. District heating in Kassel is mainly waste heat from co-generation power plants.

Thermal energy demands for space heating (SH) and domestic hot water (DHW) production represent in Germany about 90% of the total energy demands in residential buildings. Exergy demands for these thermal energy demands, in turn, are small due to the low temperature level demanded for these applications. Waste heat available e.g. from combined heat and power production (CHP) plants is a low quality energy flow suitable for supplying the requested energy. The use of waste heat with low exergy content allows a good matching between the exergy level of the demand and supply sides and represents, thus, a very efficient manner of supplying thermal energy demands in buildings.

7.5.2. Methodological description

For the analysis of this case study dynamic energy and quasi-steady state exergy analysis have been performed using the simulation software TRNSYS (TRNSYS, 2007) with a timestep of 3 minutes. For exergy analysis an input-output approach has been followed where the exergy of the energy supplied and demanded is analysed. All energy conversion steps in between are simulated in terms of energy but not in terms of exergy. In other words, exergy flows are calculated only for the space heating and domestic hot water demands, and for the exergy supplied by the primary-side pipe, i.e. return pipe from the district heating network. Pumping energy for the secondary distribution network within the neighbourhood is also simulated dynamically and included both in terms of energy and exergy. Thus, the exergy performance is evaluated as a function of the exergy demands and total exergy inputs required to supply them. The exergy losses in each component of the supply chain are not evaluated separately.

7.5.3. Technical description

The single family houses are defined as free-standing two storey buildings with a net useful area of 184.4 m^2. U-values for the external enclosing surfaces of the building are 0.28 W/m^{2}K for external walls and 0.30 W/m^{2}K for the ground floor and 0.17 W/m^{2}K for the roof, thus representing a well-insulated newly constructed building complying with requirements from the German standard (EnEV, 2009). The specific heat transfer coefficient of the building H_T´ amounts 0.35 W/m^{2}K. Internal gains through appliances and occupants are defined with a constant value of 5W/m^2 (DIN 4108-6, 2003). Infiltration rate is regarded as 0.6 h^{-1}.

Space heating (SH) is supplied by floor heating systems operated with supply and return temperatures of 32-27°C. Small DHW storage tanks of 200 litres are considered in each house. This allows reducing peak loads for DHW supply significantly. For DHW supply in single family houses a temperature of 50°C at the outlet of the DHW supply element must be ensured at all times (AGFW, 2009). An electric heater located at the outlet of the decentralized tanks is foreseen for this purpose.

A centralized heat exchanger unit is planned to supply heat to the small neighbourhood as shown in Figure 7.14. In this way, the district heating network from the local utility company is decoupled from the building appliances and systems installed, i.e. mass flow and temperature drop in the district heating network are not directly determined by the mass flows and temperature drops in the building systems (e.g. floor heating systems). All houses are connected in parallel to the local distribution network (secondary side of the heat supply), as shown in Figure 7.14.

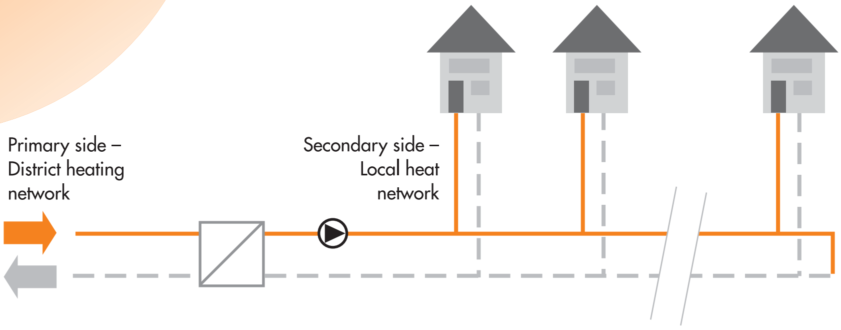


Figure 7.14: Simplified scheme of district heat supply to the studied neighbourhood of Oberzwehren (Germany).

Two different hydraulic configurations for district heat supply are investigated here, aimed at achieving minimum return temperatures to the primary net and maximum exergy efficiency in the supply. Furthermore, in order to show the benefits of low temperature district heating supply, supply via the return pipe is compared to a conventional supply using the supply pipe of the district heating network, with significantly higher temperatures.

Results for the following three options are presented (see Figure 7.15):

(i) Conventional high temperature district heating supply (via DH supply pipe).

(ii) Low temperature district heating supply (via DH return pipe), with one heat exchanger for combined domestic hot water and space heating supply.

(iii) Low temperature district heating supply (via DH return pipe), with two heat exchangers for supplying domestic hot water and space heating separately.

Figure 7.16 shows the specific annual final energy (a) and exergy (b) supplied in the three options analyzed. Pumping energy for the secondary side and power demand for the instantaneous electric heater for DHW supply represent a marginal input as compared to the thermal energy supplied to the network. The energy supply is very similar in the three cases (Figure 7.16). Differences in the total energy supplied amount only around 2% between the cases studied.

In turn, the exergy supplied is significantly different for the three systems. Case (i) in Figure 7.15, representing a conventional high temperature supply at 95°C, has the highest exergy input of the three cases with 15.3 kWh/m2a. In turn, a supply with the same hydraulic configuration but with lower supply temperatures (case (ii), 50-65°C) shows an exergy input of 12.7 kWh/m2a, representing a reduction of 17% in the final exergy input as compared to case (i). This shows the importance of reducing supply temperatures in district heating networks for increasing their exergy performance.

Supplying the DHW and SH demands separately, i.e. with separate heat exchangers and secondary networks, allows minimizing primary side return temperatures to the district heating network. Average annual return temperatures for the primary side are 42.8°C and 37.9°C for cases (ii) and (iii) respectively. Thereby, final exergy input required is again reduced in case (iii) to 11.6 kWh/m²a, repre-

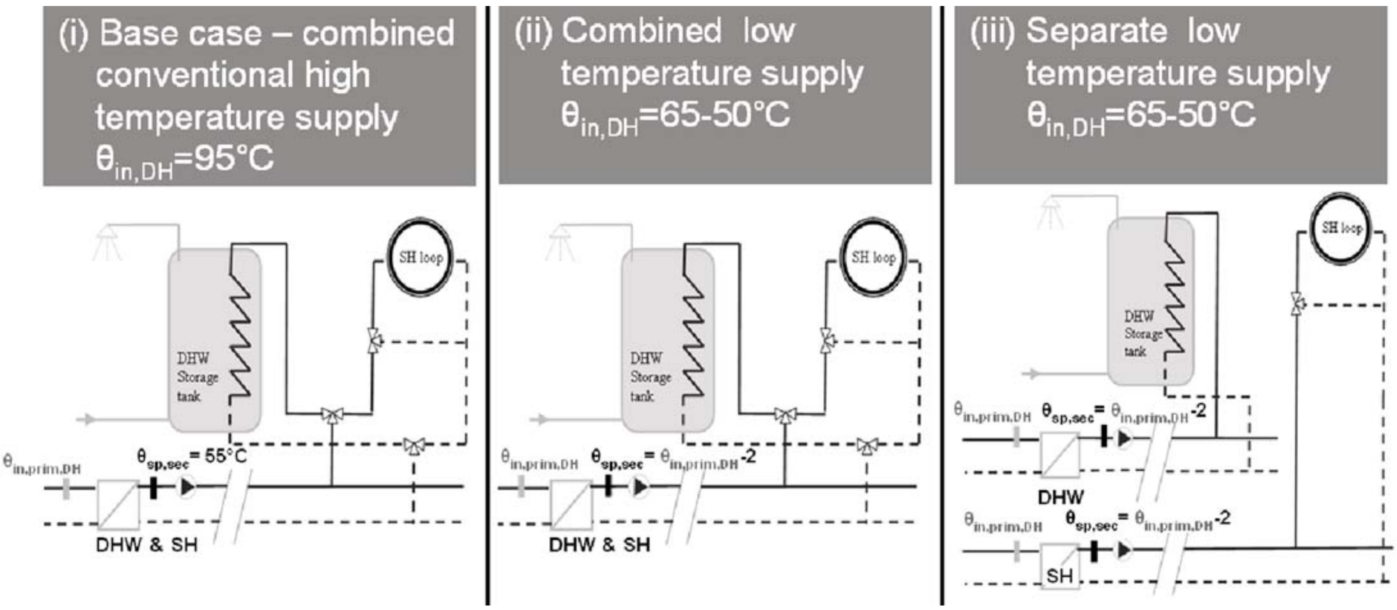
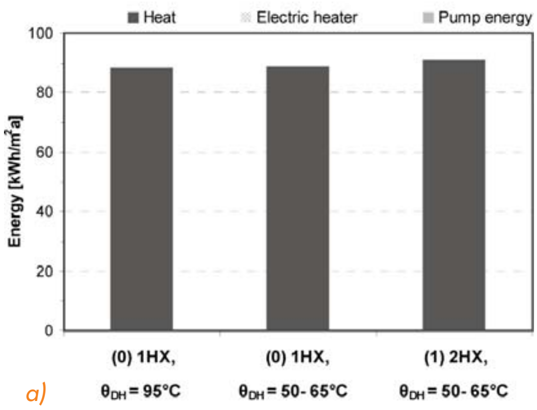


Figure 7.15: Simplified hydraulic schemes for district heat supply in the three options studied here. The schemes show the centralized heat exchanger unit(s) for providing heat to the local distribution network and the configuration of DHW and SH supply in each house.



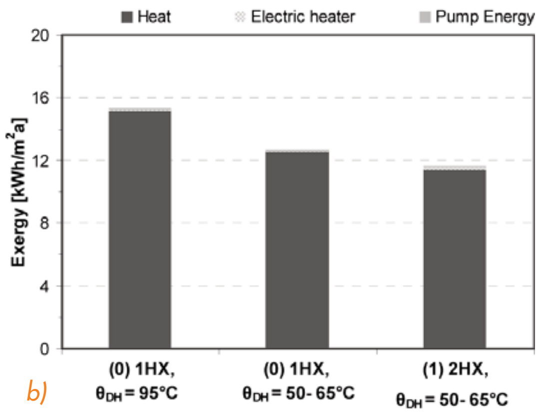


Figure 7.16: a) Specific final energy supplied in the three cases studied; b) specific final exergy supplied in the three cases under analysis.

senting a decrease of 24% as compared to case (i). This shows the influence of minimizing return temperatures for increasing the exergy performance of district heating systems.

7.5.4. LowEx Highlights and Diagrams

7.5.4.1. LowEx Highlights

In the project the utilization of a low exergy supply source, i.e. waste heat from CHP units is investigated. Based on dynamic exergy assessment performed best case scenarios and hydraulic configurations have been derived. This shows clearly the added value of exergy analysis against conventional energy assessment. In order to ensure minimum supply of high exergy sources for DHW supply, hydraulic configurations which ensure maximum supply from the district heating network for this demands have been analyzed. Furthermore, low temperature heating systems have also been implemented in the buildings.

7.5.4.2. LowEx Diagrams

In this section all energy supply options originally considered for the project are shown. Besides, the waste district heat supply analyzed above in detail and proposed as final supply system is shown. Figure 7.17 shows the Primary Energy Ratio and Exergy efficiency for the different energy supply option. A graphical representation of the quality levels of the energy demanded (energy use) and supplied is shown in Figure 7.18.

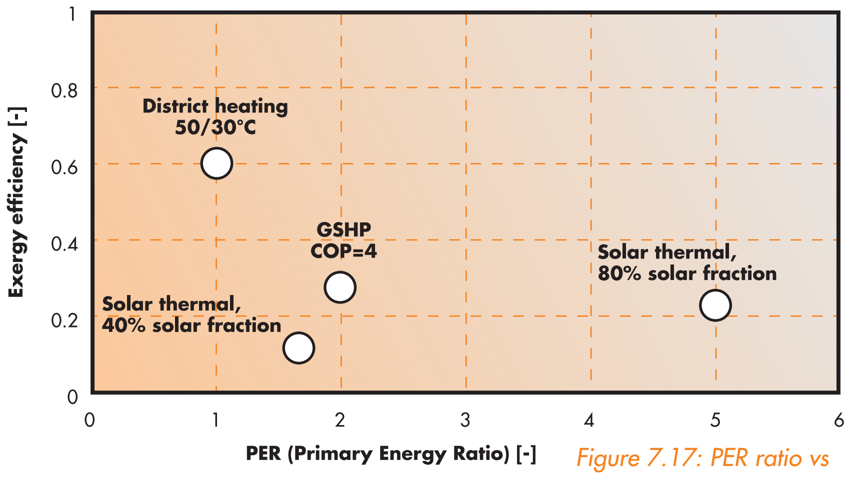


Figure 7.17: PER ratio vs exergy efficiency diagram for the different energy supply options under consideration for the community of Oberzwehren

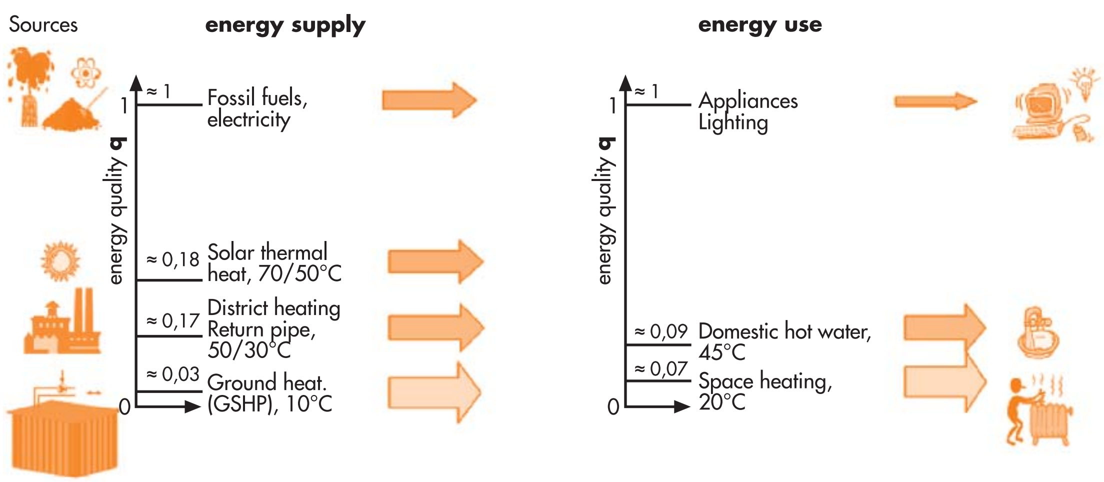


Figure 7.18. Matching of the quality levels of energy demand and supply for the community of Oberzwehren. The different energy supply options regarded as possible supplies are characterised separately.

Figure 7.19: Okotoks complex (Canada).

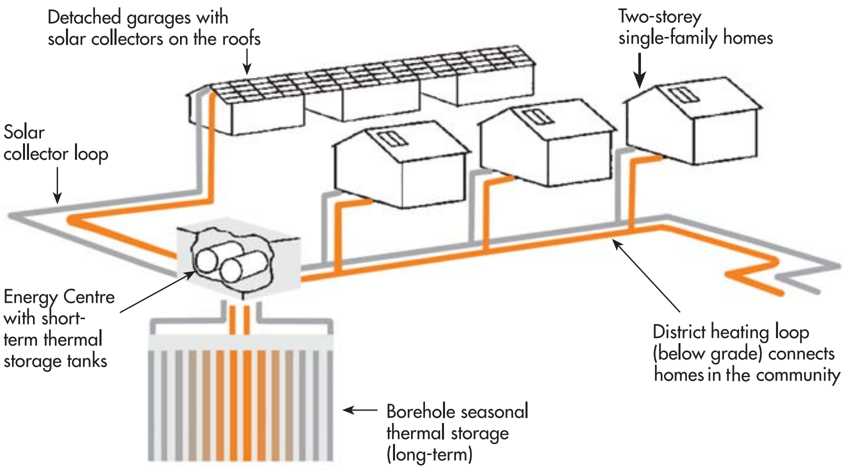


Figure 7.20: Solar seasonal storage and district heating loop used as energy supply system.

7.6. Okotoks (CA)

7.6.1. General description

The community of Okotoks (Figure 7.19), Alberta, is more than 1,000m above sea level, but its average summertime temperature exceeds 20°C. This allows solar thermal collectors, facing due South at an angle of 45°, to generate up to 1.5MW (thermal) to heat the buildings at 55°C. A detailed description of the installed system is shown in Table 7.3.

The plant started operation in June 2007 and it is estimated that it will take three years to fully charge the underground storage to 80°C. Construction of the 52 homes is complete and all homeowners have moved in. Performance indications from May 2008 suggest that the solar energy system is performing as designed and that the 90% solar fraction will be achieved by year 5.

7.6.2. Methodological description

The solar water heating system uses flat plate solar collectors and provides at least 90% of the annual space heating and 60% of domestic hot water (DHW) for the 52 individual dwellings. This was achieved, despite winter temperatures of -33°C. In Figure 7.20 a scheme of the solar thermal system, the borehole seasonal thermal storage and the district heating loop is shown.

7.6.3. Technical description

In addition to the STTS there is a long-term Borehole Thermal Energy Storage (BTES) which contains

Table 7.3: General project and system data for Okotoks case study.

GENERAL PROJECT DATA			GENERAL SYSTEM DATA	
Municipality	Okotoks, Alberta		Building Number	52
Constructor	Sterling Homes Installer		Heated Area	240 m² (each)
Installer	Solar panels	Enerworks	Specific heat load	5.46 kWh/m³
	Fancoils	Nu-Air		
	District Energy	FVB Engineering	Supply Temperature	55°C
	Thermal Storage	IFTech	Return Temperature	32°C
International	Design Team	Natural Resources Canada SAIC Canada, Enermodel Engineering	Annual Solar Resource	6.1 GJ/m² (1690 kWh/m²)
			Solar Collector Area	2300 m²
			Solar Peak Output	1.5 MWth
			Annual Collector Efficiency	29% (60-70% summer)
Hand-over	2007		Solar Delivered to Storage	1.6 GJ/m² (455 kWh/m²)
			Solar Delivered to Load	1.0 GJ/m² (284 kWh/m²)

144 boreholes. Each contains a single U-tube grouted in place. Above them, layers of sand and insulation and a waterproof membrane, are topped by clay and landscaping. The BTES is connected as 24 strings of six boreholes in series and divided into four circuits preventing the loss of any string or circuit from having an impact on storage capacity. By the end of a typical summer, temperature in the earth surrounding the boreholes is expected to top 80°C. When the STTS temperature exceeds that in the BTES, pumps circulate hot water from the STTS through the boreholes.

Because a power cut may overheat the glycol loop an additional photovoltaic (PV) array and battery bank is incorporated to power the pumps. In winter, with no glycol circulation, parts of the loop can cool down to below freezing. On start-up therefore, the glycol solution is recirculated through a bypass loop until its temperature exceeds the STTS. This protects the heat exchanger in the Energy Centre from freezing. In winter, whenever the temperature in the STTS is lower than of the BTES, the system reverses and heat is transferred from the BTES to the STTS and to a heat exchanger and the district heating loop. This supplies heated water to individual houses and the specially designed low temperature air-handler units in the basements (Figure 7.21). Warmed air is distributed through the house via internal ductwork.

7.6.4. LowEx Highlights and Diagrams

7.6.4.1. LowEx Highlights

In the project solar thermal heating systems coupled with seasonal ground thermal energy storage are planned to be used for heating purposes in a residential area. Both thermal energy ground storage as well as solar thermal heat have low temperature levels and are therefore suitable LowEx sources for supplying heating demands in buildings.

7.6.4.2. LowEx Diagrams

Figure 7.22 shows the Primary Energy Ratio and Exergy efficiency for the energy mix used at the Okotoks Drake Landing Solar community.

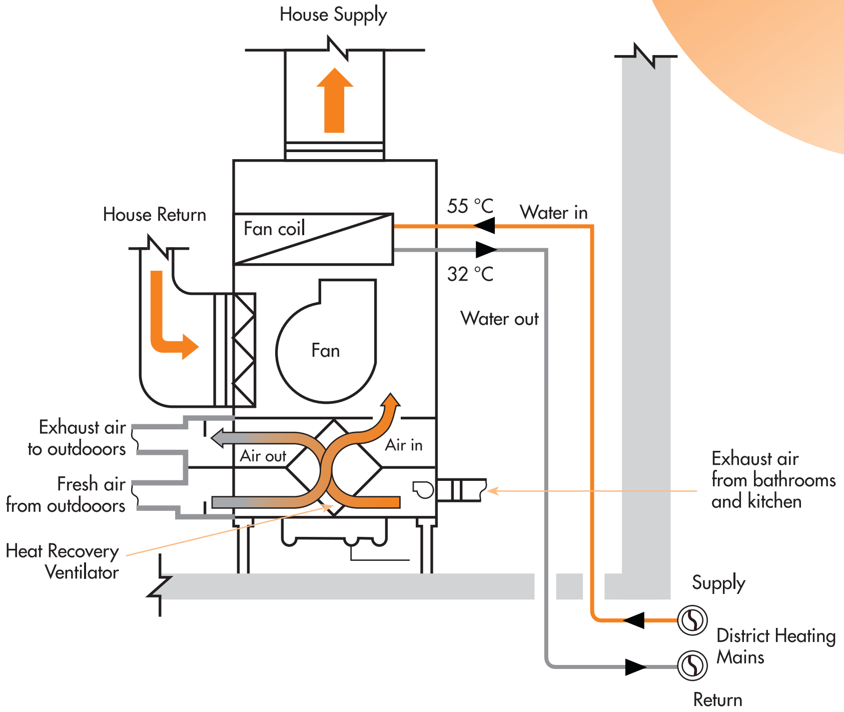


Figure 7.21: Heat emission: low temperature cooling air fan coils

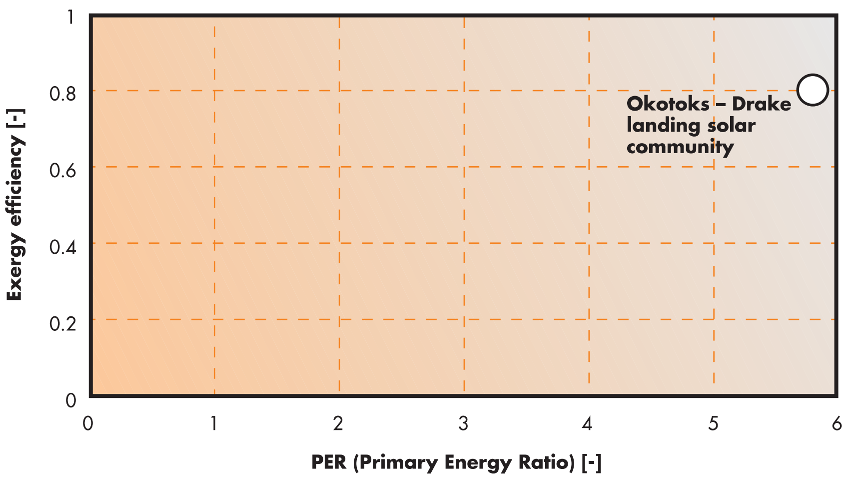


Figure 7.22: PER ratio vs. exergy efficiency diagram for the energy supply mix in the Okotoks Drake Landing solar community.

7.7. Parma (IT)

7.7.1. General description

Parma is located in Northern Italy's Emilia-Romagna region and has a population of approximately 178,000 people and a balanced presence of the tertiary, industrial and agricultural sectors, a mild climate and a notable historical buildings stock and cultural heritage. With these features, Parma represents a typical city of the Pianura Padana.
Parma in recent years has undergone many initiatives related to energy efficiency, with two energy plans (the last date back 2006), local regulations for mobility, and a mandatory building energy regulation with advanced quality certification tools and incentives for low energy and renewable energy technologies implementation.

7.7.2. Methodological description

An important aim of the work is to modify energy choices in order to optimize energy and exergy efficiency. Renewable energies, distributed generation, micro-cogeneration and micro-trigeneration may represent important measures to that end.

In order to evaluate the quality and quantity of energy uses within the built environment, the performance of the whole city, sector by sector, must be considered. This holistic approach implies that during the design process not only single buildings but the whole community must be analyzed.

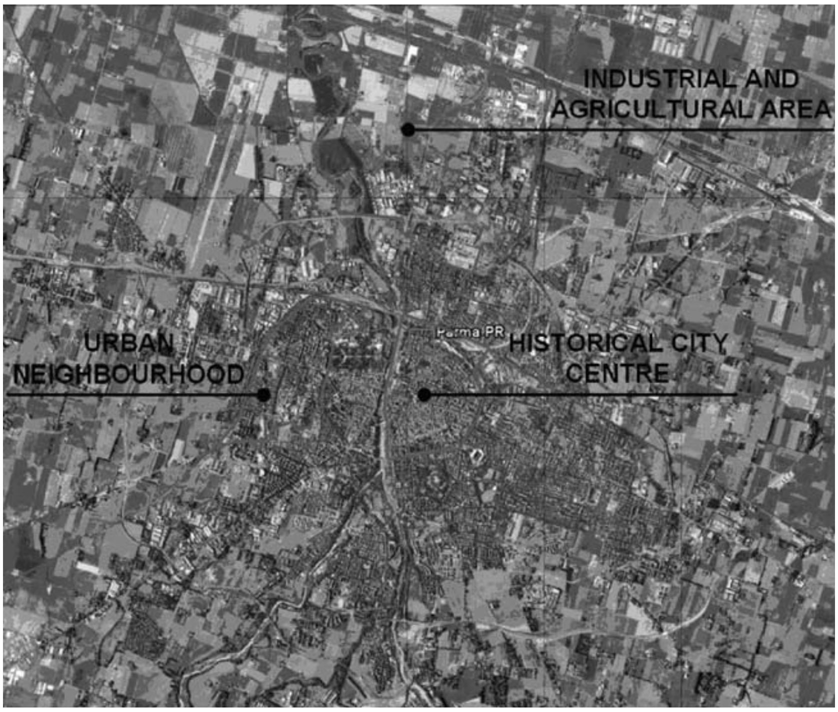


Figure 7.23: Districts that have been analyzed in the city of Parma (source: Google Earth).

This approach will emphasize the use of low energy systems and lead to better environmental and economic effectiveness, exploiting the potential of distributed local resources. This research project is leading the way in adapting energy systems to this changed paradigm.

New energy systems should address the following issues:

- the use of technologies to minimize primary energy consumption by reducing end-users demand
- the analysis of the whole energy supply chain, from generation through distribution and storage to end-users.

The aim of this study is to provide some representative experience with these issues.

In the future research will address the city of Parma as a whole. So far energy fluxes have been analyzed in detail for three different districts of the town, characterized by different energy end-uses:

- a part of the historical city centre
- an urban neighbourhood
- an industrial and agricultural area.

These districts are outlined in Figure 7.23.

Exergy loss minimization will be one of the most important objectives of this study. Here, exergy analysis focuses only on the urban neighbourhood because of its large potential for energy system optimization.

In a distributed poly-generation system electricity, high and low temperature heat and refrigerated water are produced locally. In order to efficiently support the transition towards such a system the interaction among customers' demands for energy services, available generation technologies, available renewable energy sources and utility tariffs has to be investigated. For this reason, natural gas and electricity use data were mapped in a GIS to visualize energy use pattern and identify land-use constraints that can prevent the implementation of distributed generation (Figure 7.24). Based on these real data and constraints we performed the energy and exergy analysis in order to define a realistic scenario.

For this purpose, energy demands were split into six main categories based on statistical data: electricity only end-use (appliances, lighting, etc.), electricity for refrigeration and building cooling, natural gas for water heating, building space heating, process heat (industrial sector) and natural gas only end-use (cooking, etc). Alternative strategies to supply thermal, electrical an cooling energy demands, in a poly-generation framework, were highlighted to suggest system concepts that improve energy efficiency, exergy efficiency and reduce emissions and costs. Starting from these first evaluations, hourly load profiles for electricity (utility statistical data) and thermal energy (simulated heating and cooling demand of buildings) were determined.

A multi criteria procedure, currently in development, will take into account economic, energy and exergy goals in energy systems design and optimization.
In this work three scenarios, shortly described as follows, have been analyzed for the town:

Scenario 0: Parma 2007. State of the art.
The scenario Parma 2007 is mainly based on fossil fuels used for electricity generation and heating. In fact, currently in the city of Parma fossil fuels are the only energy source. Renewable energies aren't used. The average energy demand to be assumed for further planning was based on assumption of total heat demands and heat loads. With these processed data, we were able to evaluate measures to adopt in the planning scenarios. Tables 7.4 and 7.5 present the energy characteristics and energy demands of the three analyzed districts.

Figure 7.24: GIS tool view showing the distributed generation structures foreseen for Parma city.

Table 7.4: Energy characteristics of the three analyzed districts.

	Natural gas [MWh]	Electricity gas [MWh]	Residential heated area [m²]	Residential units number	Total heated area [m²]
Historical centre	163.531	59.971	776.78	8.301	990.975
Urban neighbourhood	156.109	23.47	545.667	6.511	736.65
Industrial and agricultural area	61.454	11.164	165.615	1.956	190.457

Table 7.5: Energy demand by end-use of the buildings in the three analyzed districts.

	Heat demand				Electricity demand	
	Space heating [MWh]	Domestic hot water [MWh]	Process heat [MWh]	Other uses (cooking, etc.) [MWh]	Electric appl., lighting [MWh]	Cooling [MWh]
Historical centre	88.146	12.271	-	15.149	33.984	25.986
Urban neighbourhood	87.762	9.207	-	11.882	16.206	7.263
Industrial and agricultural area	20.627	2.787	18.69	3.569	6.094	5.069

Scenario 1: Parma 2020.

Here, the objective is to find a realistic path to reach the 2020 European goals[35] by introducing mandatory regulation for local energy planning concerning urban planning and buildings refurbishment.

Table 7.6: Scenario 1 Features and its goals.

Scenario 1 Features	Percentage
Low temperature heating systems	20%
Electricity by PV	25%
DHW from solar thermal	40%
Electricity by CHP (fossil fuelled)	25%
Renewable fraction of electricity from national grid	25%

Scenario 2: Parma 2050.

The target is to transform Parma in a renewable city[36] by the year 2050 adopting today best available technologies and practices as a benchmark. Here, the optimization of exergy fluxes will also be taken into account.

Table 7.7: Scenario 2 Features and its goals.

Scenario 2 Features	Percentage
Low temperature heating systems	100%
Electricity by PV	33%
DHW from solar thermal	60%
Electricity by CHP (50% fossil fuelled and 50% renewable energy)	67%
Renewable fraction of electricity from national grid	40%

Table 7.8: Scenario 2 Features and its goals.

DISTRIBUTED GENERATION/ ENERGY TRANSFORMATION	GRID RESOURCES	DEMAND SIDE RESOURCES
Internal Combustion Engines	Increased grid capacity	Low exergy HVAC systems
Micro-turbines	Decreased grid losses	Energy efficient Buildings
Fuel cells	Distributed storage	Solar architecture
Biomass cogeneration		Efficient lighting
Photovoltaics		Efficient electrical engines
Wind turbines		Load shifting
Mini-hydro		Efficient appliances
Heat pumps		
Absorption cooling		

7.7.3. Technical description

Today, natural gas and electricity are sold to customers by utility companies, but in a near future private investors will be increasingly involved in providing energy services. On the other hand, goals of optimizing community energy system have to be set first and must be formulated in terms of distributed energy resources potential. This can be divided into three main categories: (1) Distributed generation/energy transformation, (2) grid resources and (3) demand side measures (see Table 7.8). Measures within these categories focus on the implementation of new technologies as well as the integration of renewable energy, reduction of exergy losses in the supply chain and dynamic interaction between generation technologies and the electricity grid.

In this context, distributed poly-generation could be the new paradigma to be followed and energy efficient districts are the ideal test bed. Distributed polygeneration can be defined as the efficient combined generation, distribution and storage of energy vectors to serve different energy services demands within a district. Since the residential, commercial, industrial and agricultural sectors can be simultaneously present in a community, and specific needs have to be properly taken into account.

7.7.4. LowEx Highlights and Diagrams

7.7.4.1. LowEx Highlights

In the building energy regulation developed here use of "LowEx" technologies is strongly encouraged. Low temperature heating systems close to room temperature will be used, meaning that the energy supply will be very efficient, with minimal losses. Presently, usually high quality energy sources like oil and gas are used for heating buildings. These sources produce high process temperatures and therefore contain high levels of exergy. This exergy is wasted by using it for heating purposes that generally only demand temperatures of up to 60°C. There are, however, renewable energy sources available in large quantities that supply energy at low or moderate temperatures, like solar energy and the heating and cooling potential of underground heat exchangers. The latter In particular, have the potential to satisfy demands of buildings and can be used cost-efficiently. To utilize these sources, the overall building system has to be adjusted to low process temperatures in accordance with the Low Exergy approach. Radiant heating and cooling systems, ground and ground water heat exchange, solar thermal, as well as building envelope performance improvement (insulation, thermal capacity and natural ventilation) are suggested and economically sustained. The new building energy regulation is an example of the promotion of "LowEx" design principles at the community level (see also 5.2).

The "LowEx" measures, in this case study, include:

- Low energy demand for heating, good insulation and air-tightness
- Radiant heating systems like floor and wall heating, slab heating, capillary tube systems
- Solar energy systems for DHW
- Heat pumps

7.7.4.2. LowEx Diagrams

A graphical representation of the exergy efficiency and PER of the different supply options considered in the optimisation study is shown in Figures 7.25 and 7.26 for scenarios 1 and 2 in winter conditions. Quality levels of the demands and energy supplies are calculated by using simplified steady state equations assuming a room temperature of 20°C for heating and 28°C for cooling as well as typical supply temperatures for the technologies, sources and demands evaluated.

All calculations are done assuming a reference temperature of 5°C for winter and 32°C for summer. Supply and return temperatures considered for the solar thermal collectors and district heating return pipe are assumed to be 70/50°C and 50/30°C, respectively. Supply and return temperatures for the district cooling return pipe are assumed to be 18/25°C.

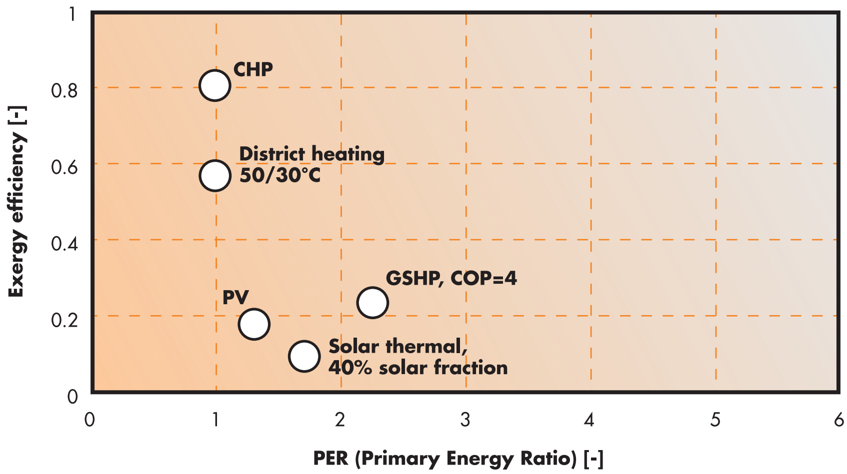


Figure 7.25: Diagram of exergy efficiency of the systems vs. primary energy ratio for scenario 1 - Parma 2020 in winter conditions.

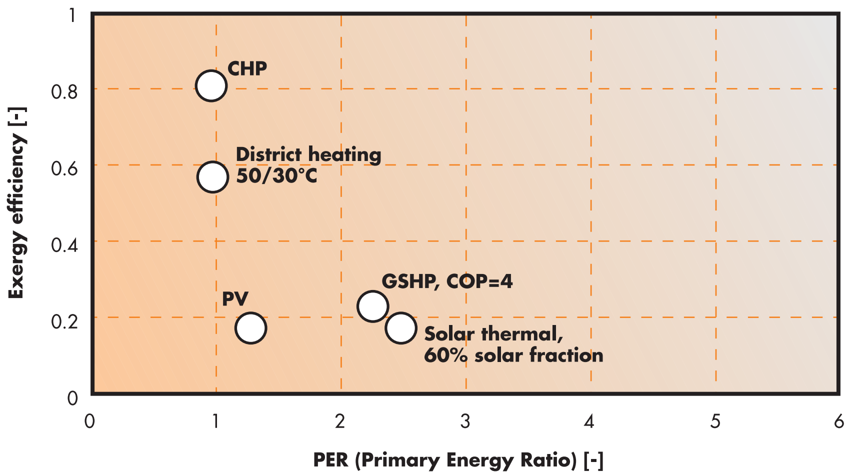


Figure 7.26: Diagram of exergy efficiency of the systems vs. primary energy ratio for Scenario 2 - Parma 2050 in winter conditions.

7.8. Twin Cities Community of Minneapolis and St. Paul, Minnesota (USA)

7.8.1. General description

The energy supply of the Twin Cities of St. Paul and Minneapolis, located in Minnesota (USA) has been analyzed on the light of exergy principle. The energy demands regarded include electrical power generation, home heating and cooling, and automobiles. Besides the analysis of energy flows, harmful emissions and ground water use were also considered. Figures 7.27 and 7.28 show how useable low quality heat is being rejected in St. Paul and Minneapolis during winter. This same practice is pervasive throughout the Twin Cities community.

Figure 7.27: St. Paul District Energy Steam Turbine Cooling Tower- Winter.

Figure 7.28: Minneapolis District Energy Cooling System Cooling Tower- Winter Operation.

Minneapolis and St. Paul receive most of their electric power from three Xcel Energy district electric power plants Riverside, Highbridge, and Black Dog. Riverside and Highbridge are natural gas fired combined Brayton and Rankine cycle plants. Black Dog is coal fired Rankine cycle. All condensing heat energy is rejected to the Minnesota and Mississippi Rivers. 25 MW of additional electric power is also generated by Evergreen Energy which supplies downtown St. Paul with electric power, district steam heating, and chilled water cooling. Evergreen Energy currently heats 80% of the commercial, residential and industrial buildings in downtown St. Paul and provides cooling for 60 % of downtown Buildings.

Minneapolis has district heating and cooling provided by NRG and Hennepin County, and the University of Minnesota also has district heating and cooling for their buildings. Hennepin County burns 1,000 t/d of municipal waste to produce 40 MW of electric power in downtown Minneapolis. No heat is being recovered at the Hennepin County garbage burning facility. Rock-Tenn, a paper recycling plant is in St. Paul, is generating 9 MW for cogeneration. A study (HVAC S.T., 2009) of Rock-Tenn facility indicates that 20.2 MW of heat energy could be recovered from the Rock-Tenn paper exhaust stack.

As a rough approximation, automobile transportation is considered essentially 100% powered by gasoline, and home heating is considered to be 100% from indirect fired natural gas furnaces.

7.8.2. Methodological description

The assessment methodology is based on a quasi-steady state model integrating thermodynamic performance of the systems analyzed. Performance is based on the set of scarce resources (energy and mass flows) required to produce all useful energy and mass flows within the community over a one year time period. All energy and mass flow interactions within the system and through the boundary are considered in terms of energy and exergy, i.e. on the light of the 2nd law of thermodynamics. Further details on the analysis methodology used for the Twin cities can be found in (Solberg, 2010).

7.8.3. Technical description

Based on exergy analysis several recommendations and modifications of the existing energy supply system as explained above have been derived. As a result, a different supply scenario based on electric cars and the use of waste heat from the power plants for district heating purposes has been developed. The main technical characteristics of this supply option are stated below.

Approximately 341 m^3/hour of water would be distributed through new distribution piping to homes and buildings throughout the city. With an average yearly temperature of 9.4°C, the Twin Cities requires heating for most of the year. In the winter all the heat rejected to the Minnesota and Mississippi Rivers by Xcel Energy power plants (1049 MW) would be used to heat 300,000 homes (with average loads of 4.4 kW). The power plant steam turbines would produce 41.7 MW less electric power due to increasing condensing temperature from 21.1°C to 71.1°C. Hot water would be distributed at 71.1°C and returned at 26.7°C.

In the summer low exergy cooling technologies such as adsorption chillers or liquid desiccant systems would be used to produce 331,000 MW of cooling. The steam turbine condensing temperature would be increased from 21.1°C to 54.4°C reducing electrical power output by 26.1 MW. Chilled water would be distributed at 7.2°C and returned at 21.1°C. District cooling would be significantly more efficient than air cooled home direct expansion condensers, creating an increase in peak electric capacity of 91 MW, representing 6% of the current capacity.

District electric would charge 88,200 automobiles batteries for 12 h/d at a rate of 1.04 kW/car. This is based on 9.7 km/litre gasoline and an efficiency of 22% fuel/engine power.

Potential heat recovery from Evergreen Energy, Hennepin County, or Rock-Tenn energy plants is not regarded in this retrofit scenario of the energy supply in the communities. Detailed data showing the loads, supply and performance of the Twin cities can be found in (Solberg, 2010).

7.8.4. LowEx Highlights and Diagrams

7.8.4.1 LowEx Highlights

The performance assessment simulation of the Twin Cities Community of Minneapolis and St. Paul demonstrates that major reductions in energy input and ground water and environmental harmful emissions could be achieved by using electric cars and modifying local power plants to recover waste condenser heat for a district heating and cooling system.

The Twin Cities community systems exergy performance can be increased by 64% from 0.465 to 0.762. Annual carbon emissions can be reduced by 39% or 1,676,000 t/a and ground water use reduced by 73% or 15,870,000 t/a. Reductions in sulphur dioxide and nitrous oxides would be of similar magnitude as carbon. A substantial amount of the emissions reduction is because power plants have significantly less emissions than do automobile engines and home furnaces.

7.8.4.2. LowEx Diagrams

In Figure 7.29 Primary Energy Ratio and Exergy efficiency for the district heat and electric power supply regarded for the Twin cities are shown. The exergy efficiency figure shown corresponds to a combined analysis of heat and power generation together, with the corresponding heat and electrical demands supplied. A graphical representation of the quality levels of the energy demanded (energy use) and supplied is shown in Figure 7.30. The height of the arrows gives an idea on the degree of matching between the energy supplied and demanded. In an ideal case supply and demand arrows would be equally thick (no energy losses) and at equal height (no exergy losses).

Quality levels of the energy supplied and demanded are calculated by using simplified steady state equations assuming a reference temperature of 9.4°C (average annual outdoor air temperature at the investigated locations), as well as typical supply and return temperatures for the district heating system planned (71/21°C). Resulting quality levels under these assumptions are displayed close to the corresponding arrows in the diagram.

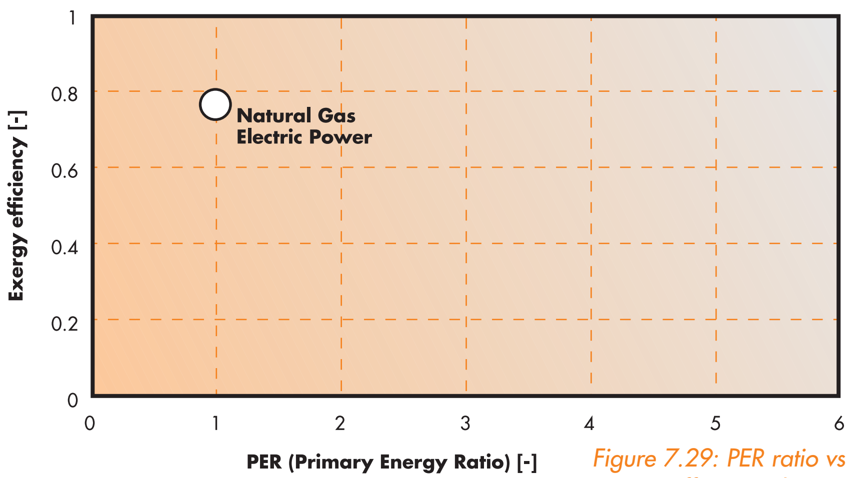


Figure 7.29: PER ratio vs Exergy efficiency diagram for the investigated supply of the Twin cities of St. Paul and Minnesota, based on district heat supply from the power plant..

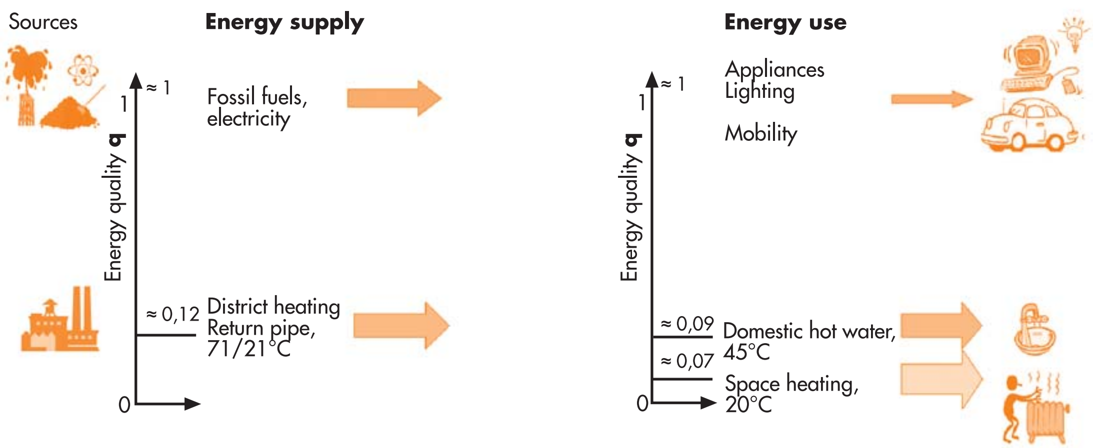


Figure 7.30: Matching of the quality levels of energy demand and supply for the Twin cities of St. Paul and Minneapolis for the described energy supply scenario.

7.9. Ullerød (DK)[36]

7.9.1. General description

The focus on energy efficiency and savings is increasing globally. The European Union energy policy gives high priority to energy savings and use of renewable energy. 40% of all energy consumption takes place in buildings, so this is one of the main target areas. In Denmark, the government has decided that energy use in new buildings must be reduced stepwise by 25% in 2010, 2015 and 2020. With the increasing number of new low-energy houses the question is: "What kind of heat supply is economically and environmentally most attractive?" In urban areas with DH, it might be reasonable to connect some new low-energy houses. But in new subdivided areas with many or only low-energy houses, it is interesting to know if it is feasible to use DH. Today in Denmark, low-energy houses located in DH districts can be exempted from connection obligation to the DH network. Therefore, it is relevant to research if DH is a good alternative to other heating technologies, e.g. heat pumps.

The low heat demand in low-energy houses means that the network heat loss may be a very significant part of the total heat demand with a traditional network design. To solve this problem, the network heat loss and involved costs must be reduced. The solution seems to be a low-temperature DH network with high-class insulated twin pipes in small dimensions (Svendsen, et al. 2005; Svendsen, et al. 2006).

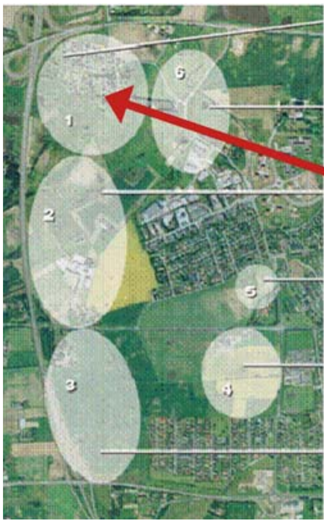


Figure 7.31: Selected area for district heating network in Ullerød-byen (Denmark).

The advantages of a low-energy DH system are:

- DH is a flexible system suitable for all kinds of energy sources
- renewable energy (RE) sources can be used directly or in combination with large-scale heat storages. This means that DH can be an important part of the future energy supply system fully based on RE
- great potential for utilisation of waste heat from CHP plants, refuse incineration and industrial processes
- DH covers a large part (60%) of Denmark's heating supply and is a well-known technology
- DH is reliable and easy to operate for the consumers.

7.9.2. Methodological description

The selected area is located in a new district called Ullerød-byen in Hillerød Municipality, Denmark (see Figure 7.31). The area has a great focus on energy efficiency regarding both buildings and energy supply. This area consists of 92 low-energy houses with an energy demand of 42.6 kWh/m²a including space heating, domestic hot water, cooling and electrical auxiliary energy.

7.9.3. Technical description

The philosophy with the DH storage unit is that lower DH temperature is required, and only a constant very low DH supply (flow) is necessary. The flow for the DH storage unit to cover the heating of spaces and domestic hot water is illustrated in Figure 7.32 for 8 different energy demand rates. The diagram represents a sort of discretized duration curve for the building under analysis.

The lowest interval covers the summer period, when there is only demand for domestic hot water. Remaining is about 7.5 months with space heating demand - "the heating season". Again, to illustrate the influence of the indoor temperature, it could be mentioned that in the theoretic case with only 20°C, the heating season is calculated to be about one month shorter.

The heat-flow rates and water flows on Figure 7.32 are very small compared to traditional units and houses. This is because the heat-flow rate to the domestic hot water is levelled out to constantly being about 0.26 kW. All fluctuations are absorbed in the tank. The low heat-flow rate at 0.26 kW corresponds to about 9 l/h in a district heating system with 50°C supply temperature and 25°C return temperature. That is only 0.15 l/min, which can be described as "one cup per minute".

The network for low-energy houses cannot be made exactly in the traditional way, because this will result in relatively large network heat losses. Lower heat losses can be accomplished through the following parameters:

- Smaller pipe dimensions
- Larger insulation thickness
- Highly-efficient PUR insulation
- Cell gas diffusion barrier
- Diffusion-tight flexible carrier pipe
- Twin pipes (double pipes)
- Reduced pipe lengths, if possible.

To optimise the pipe system with respect to costs, it has been important to look at the piping. Besides the lower heat loss, the usage of twin pipes further has the advantage of reducing the material and construction costs.

Two types of pipes are selected for the network: Flexible pipes and (bonded) steel pipes. Both types are twin pipes, which are supply and return in one casing pipe. The flexible pipes are available with dimensions of the service pipes of ø14-32 mm. Steel twin pipes in straight length of 12-16 metres are used for larger dimensions. They are available in service pipe dimensions up to ø200 mm. It should be mentioned that the ø14 mm flexible pipe is not on the Danish market yet, but will be developed and produced for testing in this project by a Danish manufacturer.

Several designs of flexible pipes are on the market, but in this project, it was decided to focus on a type with a service pipe of the multi-layer type containing aluminium and PEX (cross-linked polyethylene). The manufacturer uses the name "AluFlex" for this type of DH pipe. This type is combining the advantages of the smooth surface of the plastic pipe with the durability and tightness of the welded aluminium pipe. The service pipe is a sandwich construction, consisting of an aluminium pipe, coated inside with PEX and outside with PE. The aluminium core protects 100% against cell gas diffusion into the media and water vapour diffusion into the insulation. It further makes the pipe dimensionally stable during installation in the trench and during installation of the force transmitting press-couplings. Flexible DH pipes with regular PEX service pipes do not have the tightness property to avoid cell gas and water vapour diffusion.

The other type of pipe is a steel pipe, which has a pipe of steel as service pipe, which is diffusion tight itself.

The flexible twin pipes in the dimensions ø 14 mm to 32 mm as well as the straight pipes in larger dimensions are chosen as the continuously produced type with low-lambda PUR insulation and an aluminium diffusion barrier between the insulation and the PE casing. Because the insulation is encased between the outer diffusion barrier and the diffusion-tight media pipes, there will be no loss or contamination of the cell gas. The very low heat conductivity will therefore remain unchanged over time.

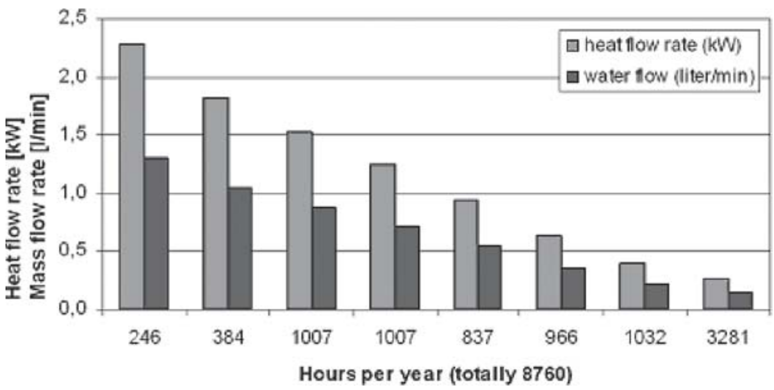


Figure 7.32: Average hourly values for heat-flow rates and water flows for the DH unit in the reference house during the year.

The DH consumption in the network depends very much on the type, size and number of connected houses. In addition, also the number of people living in the houses and their behaviour have influence on the heating consumption and network design.

It was selected to use a 145 m² one-storey house as reference house in the network. This is not a very large house, many new houses are larger, but the idea was that if it is possible to make a cost-efficient district heating system to this size of houses, then the concept will be suitable for most new houses in general. Smaller houses are being built, but they are often terraced houses, which are built closer together. That gives a higher heat density in the network system, shorter pipe lengths and smaller network heat losses per house compared to individual houses.

The selected house is a low-energy house Class 1, which refers to the building standard in the Danish Building Regulation with the so far strictest requirement to energy consumption. The space heating demand of the reference house was calculated with the simulation program "Bsim". The model of the reference house in Bsim is illustrated in Figure 7.33. Normally in theoretically calculations and for documentation of compliance with the definition (given above), an indoor temperature of 20°C is used in all heated rooms. For the reference house, it gives a theoretical heating demand of 3028 kWh per year (20.9 kWh/m²a). In practice, the conditions often are different, though. More realistic temperatures are assumed to be 24°C in bathrooms and 22°C in the rest of the house. This may not seem like a big difference, but in a low-energy house, it gives a significantly increased heating demand compared to the total demand. With the higher room temperatures, the energy demand for space heating in the house is 4450 kWh per year (30.7 kWh/m²a), which is almost 50% higher than for the case with 20°C in all rooms.

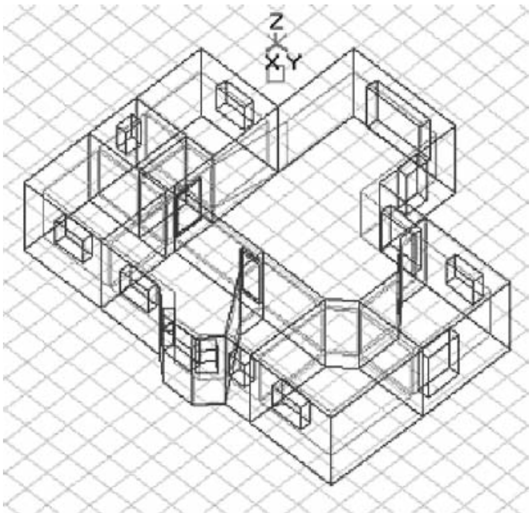


Figure 7.33: Bsim-model of reference house..

To get the total district heating demand for the reference house, it is necessary also to define the domestic hot water demand. Based on statistics and experience, the demand is specified to be 2300 kWh per year, which corresponds to about 155 litres per day of 45°C hot water.

In total, the yearly average heating demand of the reference house is calculated to be 6750 kWh (see Table 7.9), where space heating accounts for 66% and domestic hot water for 34%.

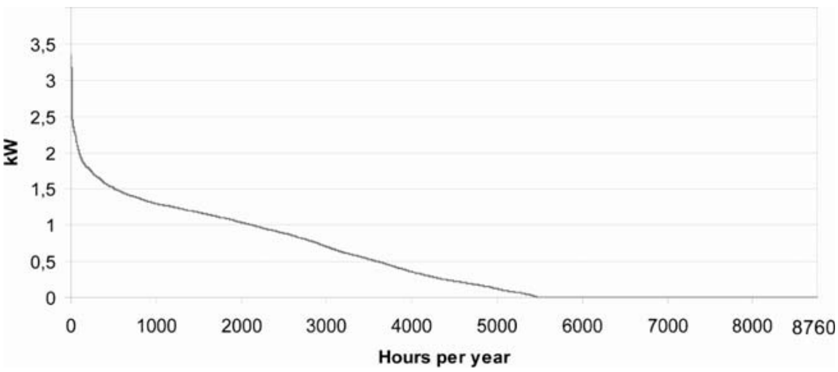


Figure 7.34: Duration curve with the hourly averaged space heating demand in the reference house (145 m²) for the local Danish climate.

Table 7.9: Total heating demand for the reference house.

Heating consumption	kWh/a
Domestic hot water	2300
Space heating	4450
In total	6750

The range of space heating demand during the year is illustrated in Figure 7.34.

It is seen that the peak demand (coldest day of the year) is 3.4 kW. Daily averaged values would be a little lower and could be acceptable for houses with floor heating, because such a building construction can accumulate the heat and therefore counteract large indoor temperature drops. In order not to lock the concept on houses with floor heating in all rooms, it was decided to use the hourly averaged values.

Table 7.10: The method and the main overall assumptions used for calculating the socio-economy are given by the Danish Energy Authority.

Main overall assumptions	Economy calculated for a 30-year period
Real interest rate	6%
District heating price in 2008	9,304 €/GJ (33,285 €/MWh)
Electricity price (household) in 2008	97,686 €/MWh
Electricity price (company/plant) in 2008	87,636 €/MWh

Table 7.11: Specific assumptions for low-energy DH.

Main overall assumptions	Economy calculated for a 30-year period
Real interest rate	6%
District heating price in 2008	9,304 €/GJ (33,285 €/MWh)
Electricity price (household) in 2008	97,686 €/MWh
Electricity price (company/plant) in 2008	87,636 €/MWh

Table 7.12: Component prices and data for the heat pumps are delivered by a Danish manufacture. Costs of DH plant and power plant capacity are included in the energy prices. National values from the Danish Energy Authority are used to calculate the costs of fuels, taxes and emissions.

Specific assumptions for ground coil heat pump		Specific assumptions for air-to-water heat pump	
Season Performance Factor	3:1	Season Performance Factor	2.5
Lifetime, consumer unit and house installations:	30 years with 50% re-investment every 10 years (2,690 €)	Lifetime, consumer unit and house installations	30 years with 50% re-investment every 10 years (2,690 €)

The socio-economic results for comparison are given in Table 7.13. The calculation is made for a 30-year period, and assumed necessary re-investments are therefore added to the investments.

Table 7.13: Socio-economic costs in a 30-year period for three scenarios [€].

Costs per 30 years [€]	Scenarios		
	Low-energy DH unit	Heat pump, ground coil	Heat pump, air-to-water
Investment and re-investment	1,187,194	1,708,912	1,443,88
Maintenance and operation	25.254	0	0
Fuel, taxes, emissions etc.	454.205	337.75	337.753
In total	1,666,654	2,046,670	1,862,690
per house	18.115	22.25	20.246

With the used assumptions, it is a fact that low-energy DH is competitive with the heat pump technology. The first results of this project indicate that an optimized DH system for low-energy houses is competitive with other heat sources from a socio-economic point of view.

Main parameters for traditional DH system design have been reviewed and in some cases adjusted. The case study illustrates that in theory it is possible to obtain a low network heat loss despite the low heat demand of the buildings regarded.

7.9.4. LowEx Highlights and Diagrams

7.9.4.1. LowEx Highlights

In the project three “LowEx” technologies are compared: low energy district heating, ground source heat pump (GSHP) and air-to-water heat pump (AWHP). Furthermore, these technologies are applied to buildings that accomplish to the requirements of low-energy Class I, according to the Danish Building Code.

7.9.4.2. LowEx Diagrams

A graphical representation of the quality levels of the energy demanded (energy use) and supplied is shown in Figure 7.35.

Quality levels of the energy supplied and demanded are calculated by using simplified steady state equations assuming a reference temperature of 0°C (typical winter space heating conditions) as well as typical supply temperatures for the technologies, sources and demands regarded.

The temperature of the ground for the GSHP system is assumed to be 8°C, equal to the mean annual outside temperature of the air in Denmark. The same temperature of the source is considered for the AWHP system, since the heat pump is used both in winter season (for space heating and domestic hot water) and in summer season (only for domestic hot water). Supply and return temperatures assumed for

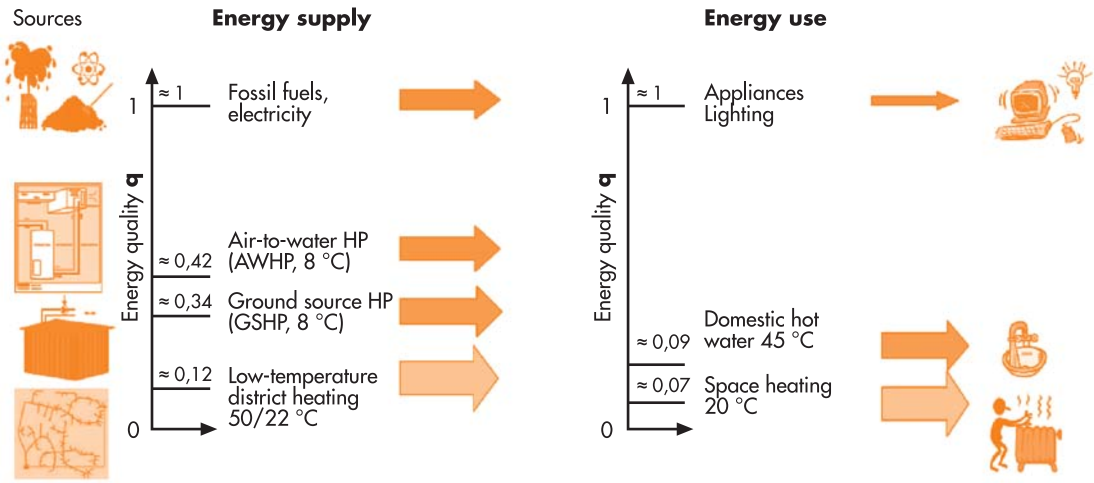


Figure 7.35: Matching of the quality levels of energy demand and supply.

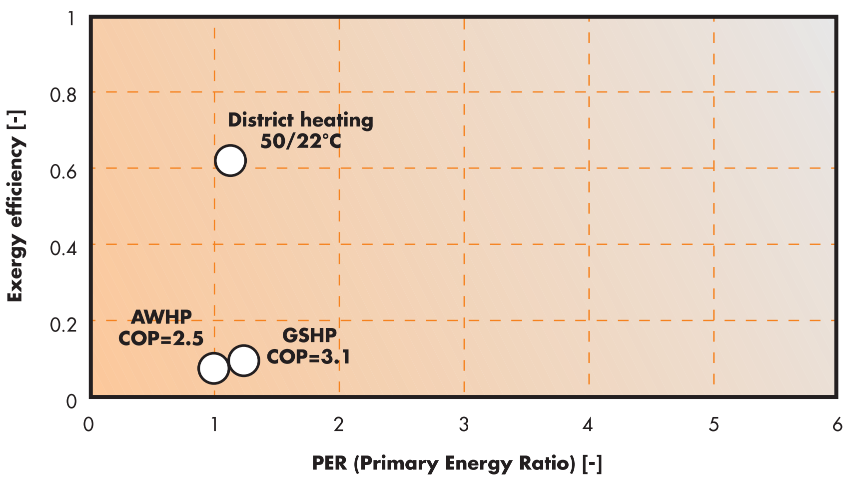


Figure 7.36: Diagram of exergy efficiency of the systems vs. primary energy ratio.

the district heating network are assumed to be 50°C and 22°C, respectively. Approximate quality levels under these assumptions are displayed close to the corresponding arrows in the diagram.

Under these assumptions, the different systems which can be used to provide the given demand can also be represented in the Exergy efficiency vs. PER below (Figure 7.36). Systems on the light grey areas of the diagram represent the best solutions from an exergy and renewable energy perspectives.

7.10. Conclusions

In this chapter results from several community case studies with innovative supply structures have been introduced. The absolute values of the exergy and energy performance of all the systems presented can not be directly compared with each other due to the different reference temperatures and operating conditions assumed in each case. However, the order of magnitude of the PER and exergy efficiencies can still be compared with each other to obtain a general picture on the best performing technologies for community supply systems.

Many of the cases presented use low temperature waste district heating systems as supply option. Often, waste heat from CHP plants is considered in these case studies as it is the case of Oberzwehren, Parma, Ullerød, Heerlen or the twin cities of St. Paul and Minneapolis.

Due to the low temperature level of waste heat, a great level of matching between the energy demands in the buildings and the energy supplied can be found. As a result, high exergy efficiencies, with values between 60% and 80% can be found for this technology. The exergy efficiency of this technology is, therefore, around 10 times better than that of conventional energy efficient supply systems such as condensing boilers.

Yet, also compared to other low temperature renewable options such as solar thermal systems the exergy performance of waste-heat based district heating is very promising: exergy efficiencies shown for solar thermal supply options with solar fractions of 40 to 60% are on the range of 15 to 20%. This is due to the still relatively high share of fossil fuels that need to be used besides the solar thermal systems. Only if very high solar thermal fraction are achieved, such as the 90% solar fraction obtained in the Okotoks project, high exergy efficiencies (of around 80%) are achieved.

With exergy efficiencies between 10% and 30% GSHP can neither compete with waste district heat or solar thermal supply with high solar fractions in terms of exergy performance. Only if heat pumps are used in combination with very low temperature lifts, i.e. with low temperature environmental energy sources or reservoirs (such as minewater or lake water, as the projects of Heerlen, Letten and Andermatt) comparable exergy efficiencies can be expected for this systems.

This shows the great potential that waste heat has as a supply technology for energy demands in buildings. Exergy analysis also shows that heat pump technologies should be used in innovative designs maximizing the exploitation of low temperature environmental sources or heat reservoirs available, in order to achieve high exergy efficiencies. Additionally, the strong necessity and importance of aiming at high solar fractions (above 60% or even on the range of 90%) is also clearly highlighted with the exergy performance figures.

[35]Reach 2020 goals for EU countries means cutting greenhouse gas emissions by 20% from 1990 levels; a 20% share of renewable energies in EU energy consumption (17% for Italy); cutting energy consumption by 20% through improved energy efficiency.

[36]Not totally renewable but almost entirely fuelled by renewable energy.

[37]This case study has been kindly supplied to the Annex 49 working group by Sven Svendsen from the Department of Civil Engineering of the Technical University of Denmark as guest participant.

8. CONCLUSIONS

The thermodynamic concept of exergy allows depicting how the potential of a given energy flow is used, or lost, respectively, in the course of an energy conversion. Thereby, inefficiencies within energy supply systems can be pinpointed and quantified. Applying the exergy method to energy systems in buildings can contribute to increasing their efficiency significantly.

Within the ECBCS Annex 37 low exergy systems were defined as "heating or cooling systems that allow the use of low valued energy as the energy source" with a focus on space heating applications. However, the scope of ECBCS Annex 49 includes the various energy demands in buildings as well as the integration of multiple buildings in communities or neighbourhoods. Thus, within the course of research activities in ECBCS Annex 49 the definition has been extended to apply to this broader context. In this sense, low exergy systems are defined as "systems that provide acceptable thermal comfort with minimum exergy destruction". This allows to find the optimal match between quality (i.e. exergy) levels of supply and demand for any use or appliance within buildings.

The basis for exergy analysis in buildings is a commonly accepted and scientifically grounded methodology. Developing such a methodology was one of the main working items within ECBCS Annex 49 activities. Results are presented in chapter 2 including a detailed description of the methodology that can be applied to both, heating and cooling processes analysis.

To obtain coherent and meaningful results, the sign convention adopted for energy and exergy analysis is of great importance. We argue that the thermodynamic reference environment for exergy analysis in building systems should be the ambient air surrounding the building. Climatic data on a time dependent basis are required for dynamic as well as quasi-steady state assessments. Average outdoor air temperatures during the heating season can be used for first estimations on the thermal exergy performance of heating applications following a steady-state method. Simple Input-output approaches (in terms of sources and demands) can also employed to perform exergy analyses at the community level.

Quasi-steady state approaches for exergy analysis performed on the basis of results from dynamic energy simulations (or measurements) have proven to be reasonably accurate. They require less input data than a fully dynamic approach and, being simpler, are less time consuming. Thereby, quasi-steady state exergy analysis represents a reasonable compromise between accurateness and complexity. It can be used in exergy calculations in buildings aiming at analyzing the performance of whole building systems. However, if the main goal of the analysis is to optimize or study the performance of storage components dynamic assessments are required.

In any application steady-state exergy assessment can only be used to show the the approximate performance of a given system or get first comparisons between systems. Steady-state analysis has proven to be inadequate to obtain the absolute value of the performance of building systems, even for space heating applications. Therefore, quasi-steady state or dynamic exergy analyses are required for an accurate comparison of building energy supply systems.

Space heating and cooling systems in buildings aim to provide comfort for the occupants. Thus besides the energy efficiency, thermal comfort within buildings is the main requirement that they must meet. Due to the importance of human thermal comfort in the built environment, a whole section is devoted to the exergy assessment on thermal comfort in chapter 2.

To make the exergy approach and calculation methodology available to the public, several tools have been developed within the project. A further important step in this direction would be the development of pre-normative proposals including exergy as a performance indicator for building systems. In such a standard, the total exergy input required by a building should be limited according to state-of-the-art technologies available. In chapter 5 several concrete proposals on strategies for characterising the performance of buildings and building systems are presented.

The energy approach, both on a building and community level, intends to reduce energy demands in buildings by increasing insulation levels or increasing the air tightness of the building envelope, i.e. optimizing the building shell. The exergy approach at both levels focuses on matching the quality levels between the energy supply and demand. Therefore, it requires the use of low quality sources for low quality demands like space heating. Demands requiring higher quality levels, such as lighting, electrical appliances or mobility, would in turn need the use of high quality sources.

Exergy analysis shows that combustion processes should not be used for providing the low temperature heat demands in buildings. Fossil fuels have a high energy quality and in intelligent energy systems should be used more rationally and efficiently with respect to exergy. CHP units, providing equally high exergy outputs such as electricity, are a great example of an appropriate use of these energy sources. Similar conclusions to for biomass-based fuels: although being renewable, their exergy efficiency if directly used for space heating is extremely low. Instead, low exergy sources should be promoted for heat and cold demands in buildings. Examples of such sources are solar thermal or ground source heat.

For the exploitation of low exergy sources often high quality energy is also required, e.g. pumping or fan power, electricity for powering heat pumps, etc. These high exergy inputs also need to be minimized.

Several case studies in this report highlight the differences between energy and exergy performance of building systems such as boilers or heat pumps. They demonstrate the necessity of designing new system concepts based on the use of low temperature heat sources for low temperature applications such as space heating or cooling. Wastewater heat recovery, waste heat in district heating networks or solar thermal heat are some of the sources that should be used for meeting these demands. However, the availability of these sources varies strongly with time and often is not coupled with demand. Intelligent storage concepts, with maximum stratification and minimum mixing are therefore a key component of low exergy supply systems in buildings.

On the other hand, as energy demands for space heating and cooling are reduced, the share of other uses within buildings such as domestic hot water (DHW) demands increases. The exergy quality factor of DHW energy demand is about 13%, almost twice as high as for space heating applications. Energy systems using low exergy sources show lower efficiencies for these demands at higher temperature levels. Further research is required to design system concepts for an exergy efficient supply of DHW.

In addition, higher and lower exergy demands within a building might be supplied in sequence, following cascading principles. Cascading of thermal energy flows in buildings is a promising approach that can be directly derived from the exergy analysis. Here future research is required.

District heating grids are a promising solution for cascading available heat flows to supply different energy demands in an intelligent way. The coordinated management and control of district heating and electricity networks together with state-of-the-art storage systems can be used to maximize the exergy efficiency of the supply. How to design and manage such systems will require further research.

CHP units and heat pumps are very efficient energy systems which allow bridging heat and electricity production, making them promising technologies for future energy systems. Further research is required to develop suitable storage concepts in combination with local heat and electricity networks on a community scale in order to reduce CO_2 emissions and primary energy use within the built environment using these technologies. The integration of solar thermal systems in local district networks is also a very promising low exergy technology, as shown in the Canadian case study for Okotoks (chapter 7).

Low temperature heating and high temperature cooling systems increase the efficiency of low-exergy sources. Thus, improving building envelopes allows using surface heating and cooling systems and therefore enables the efficient and cost-effective use of low exergy sources available. Therefore the choice of emission system restricts the options for low exergy sources of energy in buildings. For example, the exergy approach shows that water-based systems are able to provide the same thermal comfort as airborne systems. However, they require much lower exergy input for pumps and fans and exergy losses in the emission process are also lower since the emission system and the desired room temperature are very close for water-based system. An exergy efficient design in such cases would necessarily begin with a change of the emission systems – an important insight especially in countries with a strong tradition of airborne systems like the USA or Canada. In turn, in countries using mainly waterborne systems, e.g. most of European, the important choices for exergy efficient building design in the choice of energy sources.

In either case, it has been shown that the exergy performance of a building does not increase significantly if the energy demand is reduced and surface heating systems are used without changing the supply structures and sources used (see chapter 4).

Within this report the methodology for exergy assessment of building systems, which was one of the main items within ECBCS Annex 49 activities, is described and applied to several building and community case studies. This represents a significant step towards a wider application of this method for building related energy uses. The application of this assessment method to further technology concepts (e.g. storage, control, cascading concepts) will help identifying optimum and suitable uses of the analyzed technologies and represents a promising field where further research needs to be conducted.

Designing energy systems with the exergy approach would increase the use of environmental heat and renewable energy sources, leading to lower primary energy consumption and CO_2 emissions. To promote all benefits shown in this report and summarized above, exergy should be included as a further indicator in building and energy regulations.

9 APPENDIX

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9.6 Subtask structure and leaders

Research activities in Annex 49 are divided in four main subtasks. In each subtask participants from different countries cooperate under the coordination of a subtask leader. Table 9.1 shows an overview of the topics covered in each subtask and the countries and institutions leading them. In Figure 9.1 the four subtasks of Annex 49 and their interdependence is shown graphically.

Table 9.1: Subtask topics and leaders in Annex 49.

Subtask	Topic	Subtask leader
A	Methodologies	Finland (VTT Finland)
B	Exergy efficient community supply structures	Canada (NRC Canada) / The Netherlands (CHRI)
C	Exergy efficient building technology	Sweden (KTH)
D	Knowledge transfer and dissemination	Germany (Fraunhofer Institute for Building Physics)

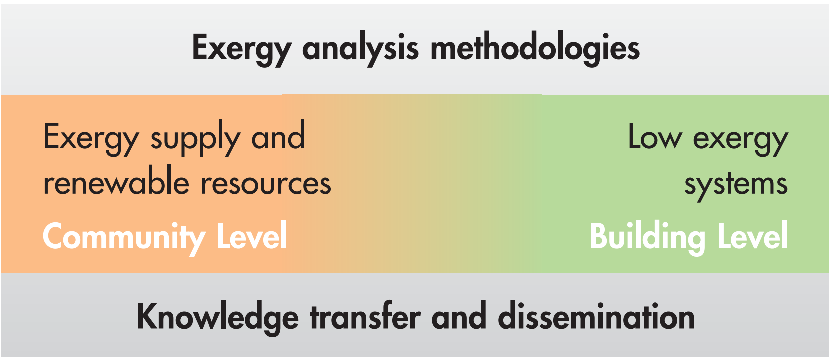

Figure 9.1: Graphical structure of the Annex 49.

9.7 ADDITIONAL INFORMATION FROM ECBCS ANNEX 49

Brochure
The brochure gives an overview of the activities of the Annex 49 working group and a short introduction of the exergy concept and its utilization within the built environment. The brochure is available in English and German.

Annex 49 guidebook: full version
A printable .pdf version of the full and extended Annex 49 guidebook, the final report of this project, is available for those who prefer to get more detailed information.

Annex 49 guidebook: summary report
The summary version of the Annex 49 guidebook, the full and extended version of the final report is available on the CD-ROM

A framework for exergy analysis at the building and community level
The Annex 49 midterm report entitled: "A framework for exergy analysis at the building and community level" gives an overview of the basic principles of exergy analysis within the built environment and about the used models for the tool development. Furthermore, some case study examples are given.

Human-Body Exergy Balance and Thermal Comfort
The Annex 49 working report on Human-Body Exergy Balance and Thermal Comfort outlines the research work with in the field of exergy and comfort. This report gives detailed information about the basics and about the modelling and the developed calculation tool.

Annex 49 newsletters
All seven issues of the biannual Annex 49 newsletter can be found on the CD-ROM. Starting from the first description of the work in the newsletter no. 1 in March 2007 to the summary of the results of the Annex 49 work in newsletter no.7 in March 2010.

Conference proceedings: The Future for Sustainable Built Environments
- Integrating the Low Exergy Approach
This conference about the future of sustainable built environments was focusing on providing front-edge results on the field of exergy analysis of buildings and communities. It was held in Heerlen/The Netherlands on April, 21st, 2009.

Conference proceedings: The Future for Sustainable Built Environments with High Performance Energy Systems
This conference about the future for sustainable built environments and energy systems integrating a maximum amount of renewable energies provided front-edge technologies and solutions for buildings, communities and energy supply. It was the final Annex 49 conference and took place in Munich/Germany on October 19th-21st, 2010.

Tools
In total, six different tools have been developed during the Annex 49 project. Ranging from a decision support tool, via a tool for a pre-design of a buildings or the assessment of a community district heating structure to a detailed building information model (BIM) based platform. Five of them are enclosed in the CD-ROM, the DPV tool has been developed to a commercial available tool, and you can find an animation about this tool on the CD-ROM.

Tool manuals
User-Guides for the enclosed five tools are available on the CD-ROM.

Technical presentations
A series of technical presentations were prepared for the biannual ECBCS Executive Committee (ExCo) meetings during the working time of Annex 49. The related presentations can be found on the CD-ROM.

Published articles
A list of the exergy related articles published by members of the Annex 49 working group during the course of the project is given on the CD-ROM.

The Network of the International Society for Low Exergy Systems in Buildings (LowExNet)
The International Society for Low Exergy Systems in Buildings (short LowExNet) has been founded on the 13th September 2003 to keep the members of the at that time ending ECBCS Annex 37 together. The main objective of this network is to formulate our interest in the regarded topics beyond the working time of the ECBCS Annex 37 and ECBCS Annex 49 itself. A large number of workshops in connection with other international events have been organised. During this often industry related workshops technologies and applications of LowEx systems on a building and community level have been presented and discussed in detail. LowExNet is intended to cover also applications in countries outside the IEA. All information about this network is available on a website (http://www.lowex.net/).

you can find the following additional information at the homepage www.annex49.com

ECBCS ANNEX 49

Annex 49 is a task-shared international research project initiated within the framework of the International Energy Agency (IEA) programme on Energy Conservation in Buildings and Community Systems (ECBCS).

ECBCS Annex 49 is a three year project. About 22 research institutes, universities and private companies from 12 countries are involved.

The main objective of this project is to develop concepts for reducing the exergy demand in the built environment, thus reducing the CO_2-emissions of the building stock and supporting structures for setting up sustainable and secure energy systems for this sector.

Annex 49 is based on an integral approach which includes not only the analysis and optimisation of the exergy demand in the heating and cooling systems but also all other processes where energy/exergy is used within the building stock. In order to reach this aim, the project works with the underlying basics, i.e. the exergy analysis methodologies.

These work items are aimed at development, assessment and analysis methodologies, including a tool development for the design and performance analysis of the regarded systems. With this basis, the work on exergy efficient community supply systems focuses on the development of exergy distribution, generation and storage system concepts.

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Annex 49
Low Exergy Systems for High-Performance Buildings and Communities

International Energy Agency
Energy Conservation in Buildings and Community Systems Programme