ECBCS Annex 49

report

Low Exergy Systems for High-Performance Buildings and Communities

Annex 49 Midterm Report

"A framework for exergy analysis at the building and community level"

International Energy Agency
Energy Conservation in
Buildings and Community
Systems Programme

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Annex 49 information based on the single reports of research items from the project.

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Cover picture:
The building Cultuurcluster "Gen Coel" in Heerlen (the Netherlands) is one of the main locations for the Minewater Project and it houses the Energy Station for that project, which is one of the main community case studies in Annex 49.
In April 2009 an international Conference on "The Future for Sustainable Built Environments - Integratign the Low Exergy Approach" organized by the Annex 49 has been hosted here.
Picture: Gerd Kleinert, Kassel, Germany

PREFACE

International Energy Agency

The International Energy Agency (IEA) 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 IEA participating 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

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

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 HEVAC 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

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 (*)

(*) – Completed

IEA ECBCS ANNEX 49

The Annex 49 is a three year international research project born as a result of the discussions in a Future Building Forum held Padova in April 2005. The project began on November 2006 and runs until November 2009. It involves 17 research institutions 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 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 structures for this sector.

Specific objectives are 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
- Promote possible energy/exergy cost-efficient measures for retrofit and new buildings, such as dwellings and commercial/public buildings
- Promote the exergy-related performance analysis of the buildings viewed from a community level

Participating countries in IEA ECBCS Annex 49: Austria, Canada, Denmark, Finland, Germany, Italy, Japan, the Netherlands, Poland, Sweden, Switzerland, United States of America

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NOMENCLATURE

Main features of the concept

A	m^2	Area
c	J/kgK	Specific heat capacity
ex	J/kg	Specific exergy
Ex	J	Exergy
F_q	-	Quality factor
h	J/kg	specific enthalpy
H'_T	W/m^2K	Specific heat transmission coefficient
m	kg	Mass
$\dot{m}$	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

Greek characters

γ	-	mass fraction
ε	-	Emissivity; Exergy effort figure
η	-	Energy efficiency
Φ	J	Heat
φ	-	Relative humidity
v	m^3/kg	Specific volume
σ	$W/(m^2K^4)$	Stephan-Bolzmann Constant
σ	-	Sensitivity of exergy analysis
ω	g/kg	Water content
μ	J/kg	Chemical potential
θ	°C	Temperature
Ψ	-	Exergy efficiency
ΔEx	J	Exergy destruction (losses)

Index

0	Reference state
a	Air
aux	Auxiliary energy (electricity)
b	Building
boil	Boiler
cc	Cooling coil
ce	Emission
ch	Charging process
chem	Chemical
coll	Collector
cw	Condensed water
d	Distribution
des	Desired
disch	Discharge process
dry	Dry
el	Electricity
env	Envelope
g	Generation
h	Heating
hc	Heating coil
humid	Humid
i	Component
in	Inlet
irrev	Irreversible, irreversibility
LMTD	Logarithmic mean temperature difference
ls	Losses
mech	Mechanical
out	Outlet
ove	Overall
p	Constant pressure
phys	Physical
prim	primary
r	Room-air
rad	Radiation
rat	Rational
ret (RET)	Return
s	Storage
sat	Saturation
simple	Simple
sol	Solar
sto	Stored
sup (SUP)	Supply
t	Time
th	Thermal
v	Ventilation
vap	Vapour
w	Water

SUMMARY

The present reports aims at outlining mid-term research outcomes within the IEA ECBCS Annex 49 international research project.

Firstly, an introduction into the use of the exergy concept for the particular case of buildings and building system`s analysis is given. Necessarily, the introduction begins with a definition of the environmental space for a system to be analysed, so-called "reference environment" in thermodynamics, which is of capital importance for exergy analysis. A brief discussion on the suitable reference environment for exergy analysis in buildings is also included. Furthermore, the importance of dynamic exergy analysis for buildings, particularly for the cooling case is highlighted, as well as the possibility and necessity of including indoor and outdoor air humidity in exergy assessments, particularly in the case of hot and humid climates.

From a literature review on the use of the exergy concept for buildings and building systems, the great importance of a unitary and common analysis framework for exergy assessment has been derived and highlighted. This is one of the main aims and objectives of Annex 49 research activities. Following, the state of the art of the method for exergy analysis in buildings as derived and used within Annex 49 activities is presented. The method for buildings exergy analysis has been widened within Annex 49 research activities, so as to be applied to energy supply structures on a community scale. The state of the art of an excel tool for community exergy analysis, which will be one of the main outcomes from Annex 49, is also introduced.

The insight on the development of the method for exergy analysis is complemented with the description of several case studies, both on a community and building level. These case studies are study objects of innovative building technologies or energy supply structures in whose design the exergy principles play a key role and where exergy analysis will be applied.

1 INTRODUCTION

The energy-related problems can be mainly grouped into two areas: the ones due to the forecasted scarcity of non-renewable energy sources like fossil fuels, potentially causing socioeconomic changes, and the ones due to the environmental impact of the use of non-renewable energy sources, ranging from the release of green-house gases to the nuclear waste disposal.

The consumption of primary energy in residential and commercial buildings accounts for about one third of the total world energy demand. Buildings represent a major contributor to energy related problems on a global scale, even though great efforts have been made to reduce energy use in buildings, for example, by improving the window glazing or constructing heavily insulated façades.

Most of the energy in the building sector is used to maintain constant room temperatures of around 20°C. In this sense, because of the required low temperature levels for the heating and cooling of indoor spaces, the quality of the energy demanded for applications in room conditioning is naturally low. The quantity of energy is given by the first law of thermodynamics, which allows obtaining energy balances in a system. The quality of energy, is given, in turn, by the combined analysis using the first and second laws of thermodynamics. From these combined analysis, the thermodynamic concept of exergy is derived. Exergy represents the part of an energy flow which can be completely transformed in any other energy form, thereby depicting the potential of a given energy quantity to perform work or, in other words, its quality. To do so, some part of exergy supplied to the system in question has to be "consumed".

In most cases, however, this low quality energy demand is satisfied with high quality energy sources, such as fossil fuels or electricity. Renewable energy sources, such as thermal solar power or using the ground as a cooling source, work very efficiently and are profitable for the regarded temperature levels.

To make energy use in buildings even more efficient and to open up the possibility of using renewable energy sources, and supplying energy with low quality, new low temperature heating and cooling systems are required. Furthermore, it has been found that by applying so-called low temperature systems, thermal indoor comfort is improved at the same cost level as by using conventional, less comfortable building service systems (IEA Annex 37, 2002).

To allow for a better understanding of energy utilisation in buildings and how to implement more renewable energy sources into the built environment, the method of exergy analyses is beneficial. A deeper understanding of the nature of energy flow and/or conversion processes in buildings would enable building designers and architects to achieve an improved overall design.

Exergy analysis, in this context, can be a necessary complement to mere energy analysis to achieve the aim of a more rational use of energy in building-related processes, as it gives deeper information about the quality of the energy used. As stated above, buildings require rather low-quality energy for space heating and cooling applications. Reductions in the quality of the energy used for these applications can be achieved by lowering supply temperatures to levels as close as possible to the demand temperature and as well by meeting their needs with low quality or low exergy energy sources. Thus, buildings are suitable to be the final part of an energy cascade, thereby making it possible to increase the exploitation degree of the energy contained in the source, whatever it may be.

As far as exergy losses are present, not all the energy potential is used. If a rational energy cascade is realized, exergy losses decrease and more energy from the same amount of fuel is utilized. According to this approach, low-exergy demands for heating, cooling ventilation and lighting in buildings are a necessary precondition towards a sustainable energy supply in buildings.

1.1 Fundamentals of exergy analysis in buildings

As stated above, the exergy of a given energy flow represents the part of that energy flow which can be completely transformed into any other energy form. Thus, exergy is the part of an energy flow which can be transformed into mechanical work (Baehr, 2005). On the contrary, the part of an energy flow which cannot be transformed into any other energy form, is designated as "anergy". From its definition it can be easily understood that it is complementary to the exergy concept. It can be written as follows:

$$\text{Energy} = \text{Exergy} + \text{Anergy} \qquad (1)$$

The exergy concept allows to depict the potential of a given energy flow to cause changes in an energy system. Therefore, an energy flow can be characterised by means of its quantity (energy) and its potential of conversion (exergy)[1].

The exergy content of an energy flow depends on the properties and state of both the system under analysis and its thermodynamic environment. Therefore, the definition of the reference environment for the analysed system plays a major role on exergy assessment. Section 1.1.1 is devoted to the detailed definition of the reference environment for the particular case of building systems.

In Table 1 several general equations for estimating the exergy content of different energy forms are shown.

The exergy concept is suitable to show how much and where the potential of an energy flow gets lost in an energy process (Ahern, 1980). The analysis of the exergy flows in energy systems is useful to assess all energy flows involved on an equal and common basis, allowing a thermodynamically correct basis for the comparison and suitability of different energy supply systems.

Table 1: Equations for estimating the exergy related to specific energy processes (Bejan, 1997; Baehr, 2005; (Shukuya and Hammache, 2002) and summarized in (Torío et al., 2009)

TOTAL EXERGY			$ex = ex_{phys} + ex_{chem}$	(2)
PHYSICAL EXERGY	**Thermo-mechanical exergy**	general	$ex_{phys} = ex_{th} + ex_{mech}$ $ex_{phys} = (h - h_0) - T_0(s - s_0)$	(3) (4)
		ideal gas	$ex_{phys} = c_p(T - T_0) - T_0\left(c_p \ln\frac{T}{T_0} - R\ln\frac{p}{p_0}\right)$	(5)
		solid/ liquid	$ex_{phys} = c\left[\left(T - T_0\right) - T_0 \ln\left(\frac{T}{T_0}\right)\right] - \nu\left(p - p_0\right)$	(6)
		humid air	$ex_{phys} = \left(c_{p,a} + \omega c_{p,vap}\right)\left[\left(T - T_0\right) - T_0 \ln\frac{T}{T_0}\right] + \left(1 + \omega\right)R_a T_0 \ln\frac{p}{p_0}$	(7)
	mechanical exergy	ideal gas	$ex_{mech} = RT_0 \ln\left(\frac{p}{p_0}\right)$	(8)
	thermal exergy	general	$Ex_{th} = Q\left(1 - \frac{T_0}{T}\right)$	(9)
		contained by a mass of room air	$Ex_{th,r} = c_a m_r \left\{\left(T_r - T_0\right) - T_0 \ln\frac{T_r}{T_0}\right\}$	(10)
		radiant exergy	$Ex_{rad} = A\varepsilon\varphi\left\{\left(T^4 - T_0^4\right) - \frac{4}{3}T_0\left(T^3 - T_0^3\right)\right\}$	(11)
CHEMICAL EXERGY		ideal gas	$ex_{chem} = \sum_i \left(\mu_i^* - \mu_{oi}\right)y_i$	(12)
		liquid water	$ex_{chem} \cong \left(p - p_{sat}\right)\nu - RT_0 \ln\varphi_0$	(13)
		humid air	$ex_{chem} = R_a T_0 \left[\left(1 + \omega\right)\ln\frac{1 + \omega_0}{1 + \omega} + \omega \ln\frac{\omega}{\omega_0}\right]$	(14)

Primary energy factors are an effort to analyse the whole energy supply process or chain of a given energy system. However, far from being fixed, they very much depend on the particular conditions of a given country and are expected to undergo strong variations as renewable energies play a greater role on the energy supply systems on a global scale. In turn, exergy analysis offers a fixed framework for evaluating different energy flows and energy sources and optimizing the use of energy sources for a given use, independently of their renewability. Hereby, a more stable and scientifically correct base for comparing different energy sources and energy systems is achieved. A combined primary-energy and exergy analysis allows depicting the share of renewable energy sources for a given use and the optimized use of the energy flows involved (Schmidt et al., 2006.

1.1.1 Reference environment

The reference environment chosen strongly determines the results of the exergy analysis. The thermodynamic reference environment of exergy analysis is the ultimate sink of all energy interactions within the analysed system, and absorbs all generated entropy within the course of the energy conversion regarded (Baehr, 2005). The environment needs to be in thermodynamic equilibrium, i.e. no temperature or pressure differences exist within it (thermal and mechanical equilibrium). Chemical equilibrium must also exist. Furthermore, the intensive properties of the environment must stay constant despite the energy and mass interactions with the regarded energy system (Baehr, 2005).

Many 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 of the energy processes occurring in the building. On the other hand, the air volume around the building can be assumed to be big enough so that no changes in its temperature, pressure or chemical composition occur as a result of the interactions with the building. However, the outdoor temperature and pressure do vary with time and space, i.e. external air is not a homogeneous system in thermo-mechanical or chemical equilibrium. Despite of this, it can be regarded as a suitable reference environment and in order to use it as such, temperature and pressure will be assumed to be uniform for the air surrounding the building (thermal and mechanical equilibrium). Concentration of different chemical species in the atmospheric air will also be regarded as homogeneous.

Rosen and Dincer (2004) evaluated the sensitivity of exergy flows as a function of different definitions of the reference environment. In Figure 1 and equation 15 the sensitivity σ of an exergy flow is shown as a function of variations ΔT_0 in the temperature T_0 of the reference environment (the so-called "reference temperature").

$$\sigma = \frac{\Delta T_0}{T_0 - T} \tag{15}$$

As shown analytically and graphically, the sensitivity of the exergy assessment is greater when the properties of the system are close to those of the reference environment. This justifies that typically a constant reference environment has been assumed for exergy analyses of power plants and industrial processes involving high quality energy forms as main output. In turn, in the built environment, energy demands happen at conditions close to those of the reference environment and subsequently undergo strong variations for changing environment and / or system conditions. This justifies establishing and applying a method of dynamic exergy analysis for the building sector.

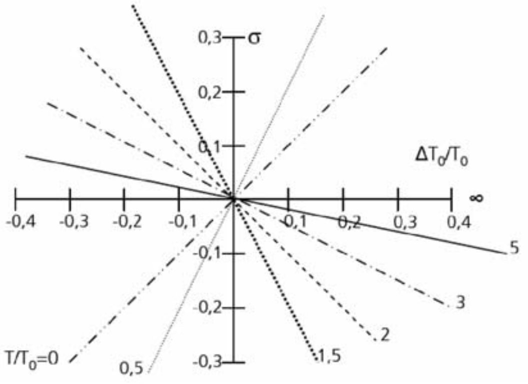


Figure 1: Variation of the thermal exergy flows for variations in the reference temperature (Rosen and Dincer, 2004).

However, in the literature mainly static exergy analysis of building systems can be found so far (Schmidt, 2004; Cervantes and Torres-Reyes, 2002; Pons et al. 1999; Izquierdo et al., 2002; Dincer and Rosen, 2007; Marletta et al., 2007; Hepbasli and Akdemir, 2004; Dikici and Akbulut, 2008; Saitoh et al., 2003; Ozgener and Hepbasli, 2007; Xiaowu and Ben, 2005; Chaturvedi et al., 1998; Koroneos et al., 2003; Torres-Reyes et al., 1998), and dynamic exergy analysis are still the exception (Alpuche et al., 2005; Angelotti and Caputo, 2007; Torio and Schmidt, 2008; Nishikawa and Shukuya, 1999; Sakulpipatsin et al., 2006; Sakulpipatsin, 2008).

1.1.2 Steady-state and dynamic exergy analysis

As stated in the previous section, the sensitivity of an exergy analysis to variations in the reference environment depends on how close the properties of the system under analysis are to those of the reference environment.

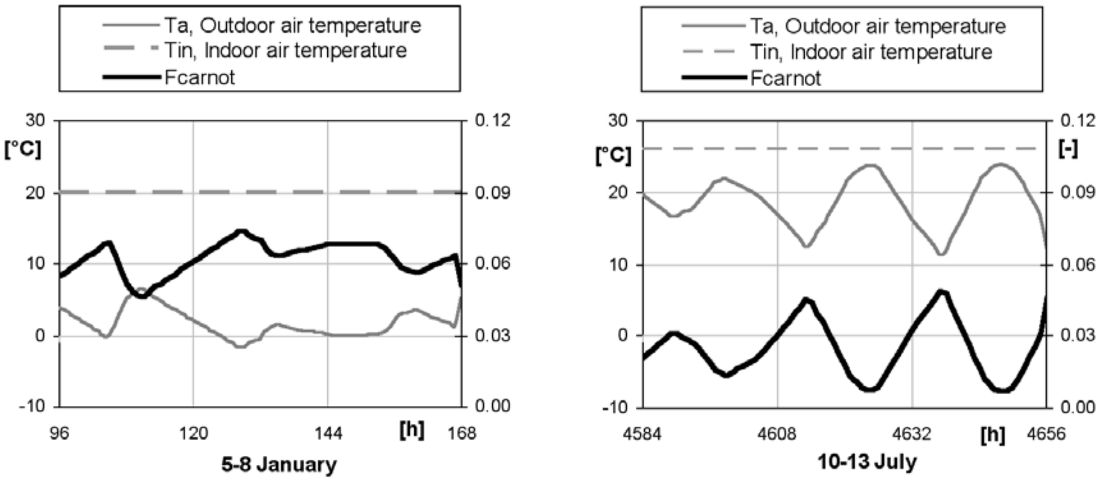
For climatic conditions in Germany and Central Europe during the heating season, indoor air temperature in buildings is significantly different from that of the outdoor air chosen as reference environment for exergy assessment. A number of authors have investigated the influence of choosing a steady-state definition of the outdoor reference environment on exergy analysis of space heating applications. If mean monthly or seasonal outdoor temperatures are assumed to be constant, the mismatch with dynamic analysis is found to be around 3-10% (Sakulpipatsin, 2008; Angelotti and Caputo, 2007).

However, under summer climatic conditions indoor air temperature is much closer to outdoor temperature. Thus, Carnot factors, and subsequently the exergy flows associated with space cooling, undergo dramatic variations for changing outdoor air conditions. As a consequence, steady-state estimations of the exergy flows for cooling applications lead to errors which can be as high as 75% of the exergy flow (Angelotti and Caputo, 2007). Furthermore, using mean outdoor temperatures for the cooling period might result in outdoor temperatures below the indoor setpoint of 26°C. Subsequently it is then impossible to estimate any cooling load.

Accordingly, 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 in milder the climatic conditions. However, exergy flows in cooling applications can only be assessed by means of dynamic analysis, where variations in outdoor reference conditions are taken into account (Torío et al., 2009).

The impact of variable climatic conditions is expected to vary with the type of energy system under analysis. For example, the exergy input and exergy losses of a condensing boiler are expected to be fairly constant even under varying outdoor reference conditions, since high quality fossil fuels with a constant quality factor or 0.94 is being used. On the other hand, the temperature of the heat output of a solar thermal system varies significantly depending on outdoor conditions and is relatively close to outdoor air temperature. Thus, strong variations in the Carnot factor associated to the exergy flow from the solar thermal system are expected and bigger mismatching between stationary and dynamic exergy analysis can be expected.

Therefore, if the goal of exergy analysis is to compare different energy systems, dynamic exergy analysis is preferable, so that errors arising from the steady-state assessment can be excluded and the differences between the energy systems can be solely attributed to improved or optimized performance.



January

July

Figure 2: Dynamic behaviour of the indoor and outdoor temperatures and the resulting Carnot factors for winter and summer climatic conditions. Climatic data correspond to Würzburg (Germany).

1.1.3 Air humidity

Differences in the air humidity of indoor and outdoor (i.e. reference) air cause physico-chemical exergy flows. If the dynamic behaviour of a building is considered, variations in the humidity content of both indoor and outdoor air usually have to be taken into account. In order to accurately determine the exergy flows on the system both thermal and physico-chemical components of the exergy flows need to be assessed.

Sakulpipatsin (2008) evaluated the influence of including air humidity in the definition of both the building system and its reference environment on the exergy flows through the building envelope. Two different climatic conditions were investigated: Bangkok (Thailand), a hot and humid climate, and De Bilt (The Netherlands), a cold and dry climate. In both cases including dynamic variations in the indoor and outdoor air humidity leads to the most accurate estimation of exergy flows. On the other hand, neglecting ambient air humidity (i.e. regarded as zero or equal to indoor air humidity), underestimates the exergy flow up to 86% in the annual total for the hot and humid climate and by about 3% in the cold dry climate.

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

1.1.3.1 Case study[2]

In order to show the differences between exergy analysis under dynamic and steady-state assumptions, results from a case study for two different climatic conditions are shown. Both dynamic and steady-state values of the indoor and outdoor temperatures and humidity ratios are considered.

The exergy of indoor air (per kilogram of humid air) at specific indoor climate conditions is investigated as a function of different outdoor climate conditions. Reference environments used for the exergy calculations are actual time-dependent outdoor climates from two cities in different climate zones. Differences in air properties (temperature, T, and humidity ratio, ω) between the indoor air and the outdoor air are variables for this study.

Indoor climate conditions used in the exergy calculations are air temperature T between 20-26°C, relative humidity RH_i between 30-60% and air pressure p equal to atmospheric pressure. The indoor climate conditions are commonly applied for an indoor thermal comfort zone. Figure 3 shows the area of the conditioned indoor climate on the ASHRAE psychrometric chart (ASHRAE, 1993).

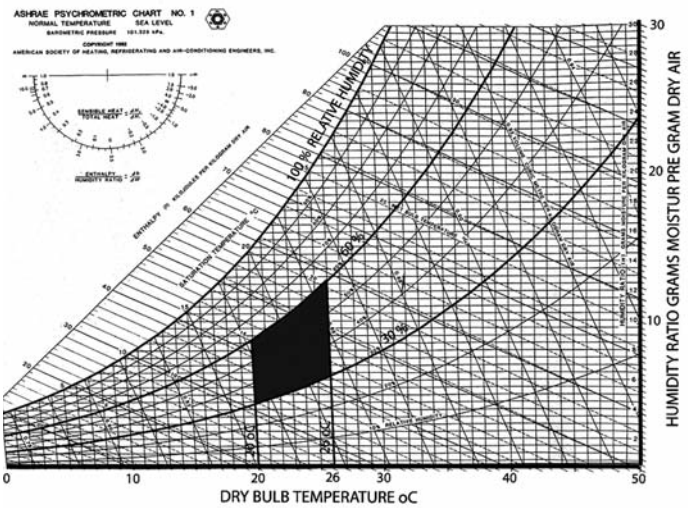


Figure 3: The conditioned indoor climate area on the ASHRAE psychometric chart.

The analysis framework considers exergy values of air in buildings, calculated by using a number of alternative reference environments, to investigate what reference environment alternative might be able to substitute the actual reference environment depending on all air properties (T, ω and P). The analysis framework also considers the exergy values of air in buildings at different levels of humidity, by assuming $\omega_i = \omega_0$ and $\omega_i = \omega_0 = _0$, with the other reference environment parameters remaining the same for indoor air as well as outdoor air. The aim is to investigate the possibility of considering indoor air and outdoor air as dry air for exergy calculations.

The exergy calculations are performed for three sets of parameters for the indoor environment and two alternative reference environments. In Table 2 the combination of parameters for defining the conditions of the indoor air and reference environment are shown.

- Case A Ex(T_i, ω_i, p_0): exergy calculation of humid air in buildings, assuming pi=p_o, i.e. neglecting pressure differences between indoor and outdoor air, using equations (16) and (17) below.
- Case B Ex(T_i, ω_0, p_0): exergy calculation of humid air in buildings, assuming p_i=p_o and ω_i=ω_0, i.e. neglecting differences in pressure and humidity ratio between indoor and outdoor air, using equation (18) below
- Case C Ex(T_i, ω_0, p_0): exergy calculation of dry air in buildings, assuming pi=po and ω_i=ω_0=0, using equation (19).

$$\mathrm{Ex}_{\mathrm{phys,humid,a}} = \left(\frac{0.62198\, c_{p,dry,a} + \omega\, c_{p,w}}{0.62198 + \omega}\right)\left(\left(T - T_0\right) - T_0 \ln\left(\frac{T}{T_0}\right)\right) + R\left(\frac{1+\omega}{34.5224 + 55.5081\omega}\right)^{-1} T_0 \ln\left(\frac{p}{p_0}\right) \qquad (16)$$

$$\mathrm{Ex}_{\mathrm{chem,humid,a}} = R\left(\frac{1+\omega}{34.5224 + 55.5081\omega}\right)^{-1} T_0\left(\left(\frac{\omega}{0.62198+\omega}\right)\ln\left(\frac{\omega}{\omega_0}\right) + n\left(\frac{0.62198+\omega_0}{0.62198+\omega}\right)\right) \qquad (17)$$

$$\mathrm{Ex}_{\mathrm{humid,a}} = \left(\frac{0.62198\, c_{p,dry,a} + \omega\, c_{p,w}}{0.62198 + \omega}\right)\left(\left(T - T_0\right) - T_0 \ln\left(\frac{T}{T_0}\right)\right) \qquad (18)$$

$$\mathrm{Ex}_{\mathrm{dry,a}} = c_{p,dry,a}\left(\left(T - T_0\right) - T_0 \ln\left(\frac{T}{T_0}\right)\right) \qquad (19)$$

Table 2: Analysis framework to study the influence of possible definitions of a reference environment to determine the exergy of air in buildings. The properties defining the state of the reference and indoor air environments are shown, as well as the combinations of them regarded here.

Outdoor environment Indoor environment	Reference environment 1	Reference environment 2
Option A	T_o, ω_o, p_o T_i, ω_i, p_i=p_o	T_o, ω_o=0, p_o T_i, ω_i, p_i=p_o
Option B	T_o, ω_o, p_o T_i, ω_i=ω_0, p_i=p_o	T_o, ω_o=0, p_o T_i, ω_i =ω_0, p_i=p_o
Option C	T_o, ω_o, p_o T_i, ω_i=0, p_i=p_o	T_o, ω_o=0, p_o T_i, ω_i=ω_0=0, p_i=p_o

Since it is assumed that there is no pressure difference between the indoor air and the outdoor air, two reference environments are defined as combinations of the air parameters T, ω, p. The reference environment alternatives considered are:

- Alternative 1 (T_o, ω_o, p_o): air temperature T_o, humidity ratio of air ωo and air pressure p_o
- Alternative 2 (T_o, p_o): air temperature T_o and air pressure p_o.

Cold and dry climate, De Bilt NL

De Bilt is located at 52°12′ north, 5°18′ east. Average, mode, median and standard deviation values of air temperatures T and of humidity ratios ω per season and for the year, are given in Table 3. These values are derived from the climate data at that site, taken from the TMY2 data (NREL, 1995).

Exergy of air in buildings in De Bilt at the first hour of the TMY is calculated by taking calculation case A with reference environment 1 (using equations 16 and 17) and using the following data. The outdoor climate data are taken from the TMY2 data (NREL, 1995).

This calculation is then repeated for each hour of the TMY year. Figure 4 shows the hourly exergy calculation results for the TMY year, calculated by taking case A with reference environment 1 (line A1) and case C with reference environment 1 (line C1).

Averages of the exergy values of air in the buildings per season and for the entire TMY are calculated from the sum of the hourly exergy calculation results are shown in Table 4.

Table 3: Air temperature and humidity ratio at De Bilt.

		Air temperature *T* [°C]			Humidity ratio ω [-]		
		Season I	Season II	Year	Season I	Season II	Year
Outdoor	Average	14.99	5.31	9.37	0.0081	0.0046	0.0061
	Mode	13.55	0.60	6.50	0.0087	0.0037	0.0037
	Median	14.84	5.35	9.34	0.0079	0.0045	0.0057
	Standard deviation	4.84	5.28	6.99	0.0020	0.0015	0.0024
Indoor	Average	20.38	20.00	20.16	0.0077	0.0051	0.0062
	Mode	20.00	20.00	20.00	0.0088	0.0044	0.0044
	Median	20.00	20.00	20.00	0.0079	0.0045	0.0057
	Standard deviation	1.17	0.02	0.78	0.0016	0.0010	0.0018

Table 4: Exergy of air in buildings in De Bilt (average values, in J/kg).

Calculation option	Reference environment alternative	Season I	Season II	Year
A (humid air)	1	85.37	439.60	291.12
A (humid air)	2	81.12	426.42	281.68
B (humid air; $\omega_i=\omega_o$)	1.2	81.12	426.33	281.63
C (dry air)	1.2	81.00	425.93	281.34

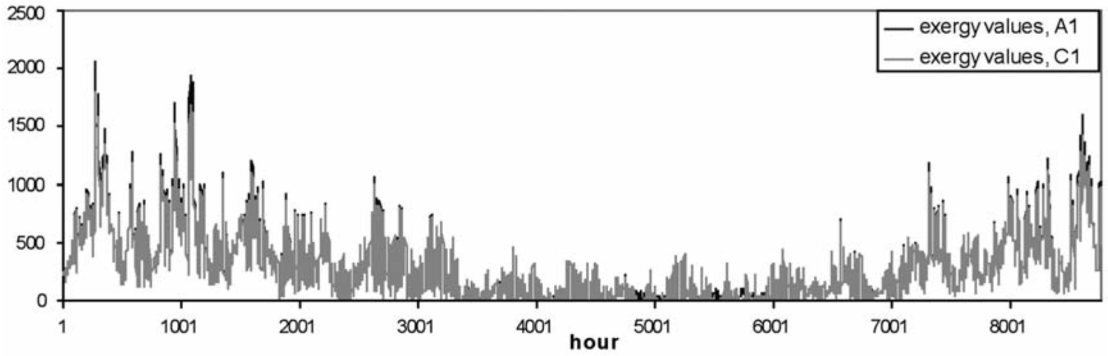


Figure 4: Hourly profiles of exergy calculation results for the TMY year (De Bilt), calculated by taking calculation option A with reference environment alternative 1 (line A1) and calculation option C with reference environment alternative 1 (line C1).

Hot and humid climate, Bangkok TH
Bangkok is located at 13°45′ north, 100°31′ east. Average, mode, median and standard deviation values of air temperatures T and of humidity ratios W at the city, per season and for the whole year, are given in Table 5. These values are derived from the climate data at the site, taken from the TMY2 data (NREL, 1995).

Average values of exergy values of indoor air in Bangkok per season and of the TMY shown in Table 6 are calculated from hourly exergy calculation results.

Table 5: Air temperature and humidity ratio at Bangkok.

		Air temperature *T* [°C]			Humidity ratio ω [-]		
		Season I	Season II	Year	Season I	Season II	Year
Outdoor	Average	28.30	27.28	27.71	0.0185	0.0166	0.0174
	Mode	27.90	27.85	26.50	0.0205	0.0150	0.0150
	Median	28.25	27.33	27.75	0.0184	0.0164	0.0175
	Standard deviation	2.70	3.37	3.15	0.0019	0.0026	0.0025
Indoor	Average	25.71	25.18	25.40	0.0126	0.0123	0.0124
	Mode	26.00	26.00	26.00	0.0128	0.0128	0.0128
	Median	26.00	26.00	26.00	0.0128	0.0128	0.0128
	Standard deviation	0.70	1.49	1.25	0.0004	0.0010	0.0008

Table 6: Exergy of air in buildings in Bangkok (average values, in J/kg).

Calculation option	Reference environment alternative	Season I	Season II	Year
A (humid air)	1	169.00	110.32	134.91
A (humid air)	2	20.17	16.71	18.16
B (humid air; $\omega_i=\omega_o$)	1.2	20.20	16.73	18.19
C (dry air)	1.2	20.11	16.66	18.10

Analysis and comparison of the results

Under the assumption of identical indoor and outdoor air pressure, considering humid indoor air (case A) with humid outdoor air as reference environment (alternative 1) leads to the most accurate determination of the exergy content of indoor air. When the humidity of the reference environment is neglected, using reference environment 2, differences in average values of the hourly exergy calculation results for season I are up to 88.1% for a hot and humid climate, but only 5.0% for a cold climate. For season II and for the whole year, differences in average values of the exergy results are low for the cold climate (3.0% and 3.2% respectively), but very high for the hot and humid climate (84.9% and 86.5% respectively). The exergy level of liquid water and that of water vapour are very different: the former is 1 million times bigger than the latter, if water molecules contained in 1m^3 are compared. Humidification and dehumidification processes are, thus, very exergy intensive. Therefore, when dealing with humid air inside, with a humidity ratio different from the reference environment, the humidity ratio of outdoor air as reference environment, ω_0, should also be regarded. This is particularly important for buildings with dehumidifying/humidifying equipment, air-cooling and also for buildings with a high occupancy level and a low ventilation rate, because of the humidity production of occupants. This highlights the importance of natural ventilation systems coupled with rational radiative cooling systems in low-exergy optimised building design.

Exergy calculations using cases B and C with reference environment 1 gives similar exergy results, since average values of ω, per season and of the year, are very small at less than 0.0101.

When the humidity is assumed to be identical for indoor and outdoor air (case B), which will be the case of well-ventilated buildings with a low occupancy and hence a low water vapour production, it is not necessary to choose humid air as the reference environment. A reference environment consisting of dry air is accurate enough and the indoor air itself may be considered as dry air too (case C). These results are valid for both the hot-humid (Bangkok) and cold-dry climate (De Bilt).

Exergy calculations for a cold country might be done by using only environmental temperature as a characteristic of the reference environment, and assuming that the outdoor air and indoor air are dry. For a hot and humid country these assumptions could lead to very large discrepancies and are therefore not recommended.

1.1.4 Input-Output approach

In order to improve the efficiency 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 4701-10:2001, EnEV:2007, DIN 18599:2007, CEN EN 13790:2004). For this the energy supply chain in buildings is divided into several subsystems. Figure 5 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 (Schmidt 2004) in the framework of the IEA ECBCS Annex 37 program. The tool has been improved and enhanced within the frame of the Annex 49. The calculation method and corresponding equations used in the tool are presented in section 1.2.

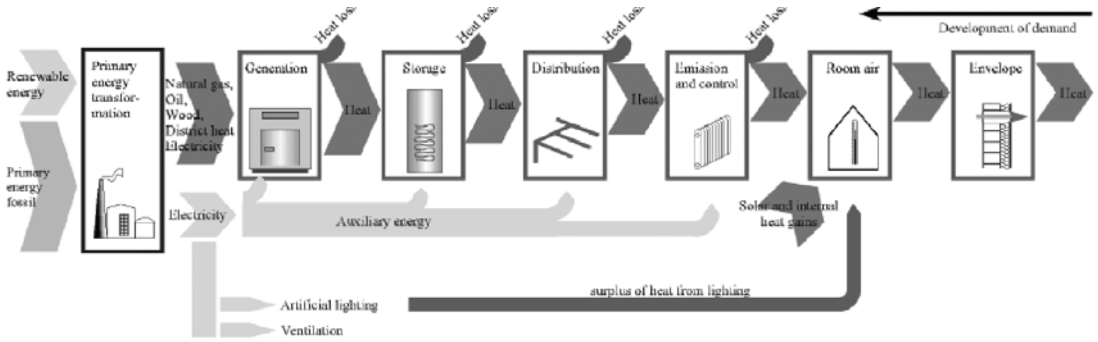


Figure 5: Energy supply chain for space heating in buildings, including from primary energy transformation into final energy, all intermediate steps until the supply of the building demand (Schmidt, 2004).

All the 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 Excel tool, optimization of single components which might have a negative influence on other steps of the energy supply process is avoided.

1.2 Method for exergy analysis in space heating applications[3]

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 Shapiro, 1998).

The energy supply chain of buildings is divided into subsystems (Figure 5). Below the equations and exergy balances for each of the subsystems are presented, starting with the outermost subsystem, the building envelope and progressing inward (from right to left in Figure 5). For each subsystem, a figure shows the boundaries for the combined and analyzed systems regarded for the exergy, balance. The boundary of the combined system is represented as a slashed line, whereas the boundary for the analyzed system is a dotted line. The equations for the subsystems are taken from or based on those presented in Schmidt (2004).

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.

Equations derived here assume steady-state conditions for the energy processes. As stated in section 1.1.2 stationary assessment of the exergy flows is associated with relatively high inaccuracies, particularly in the case of space cooling. However, if steady-state equations for the exergy assessment are used in combination with dynamic energy analysis software, a quasi-steady state exergy analysis can be performed.

1.2.1 Building Envelope

The net heating demand of the building, $\Phi_{h,b}$, is considered as the energy flow through the building envelope. This is equivalent to the active heating demand left once the internal and passive gains of the building are taken into account. It will be assumed that the heat flow takes place at constant indoor air temperature. In the case of dynamic simulations, variable indoor temperatures for each time step would be assumed.

Exergy of the energy stored in the wall construction as the heat flows through the building envelope, $Ex_{sto,env}$, will be considered part of the exergy losses due to the heat transfer (equation 20).

$$Ex_{in,env} = \underbrace{Ex_{out,env}}_{\approx 0} + \underbrace{\Delta Ex_{irrev,env} + Ex_{sto,env}}_{Ex.consumed = Ex_{ls,env}} \qquad (20)$$

Investigations show that the simplification of assuming a quasi-steady state instead of fully dynamic behaviour on the wall implies inaccuracies in the range of 1% for the space heating case and German climatic conditions.

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 (see section 1.1.1). The corresponding exergy is calculated according to equation (21)

$$Ex_{in,env} = Ex_{ls} = \Phi_{h,b}\left(1 - \frac{T_r}{T_0}\right) \qquad (21)$$

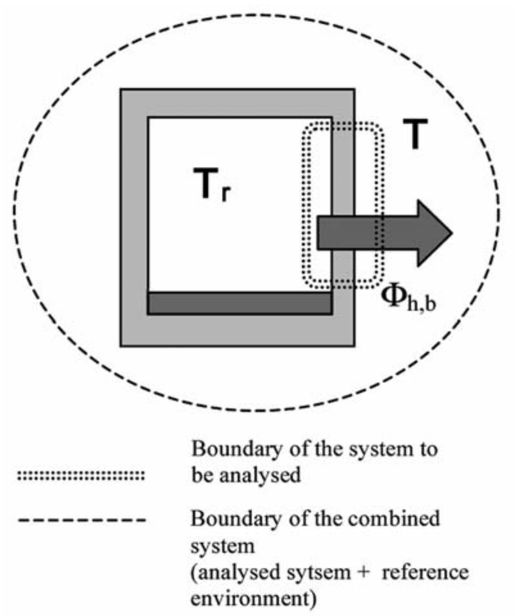


Figure 6: Energy flows, temperature levels and boundaries for the building envelope subsystem.

1.2.2 Room-air

The room is heated either by air heating or by a warm surface, as assumed here. The temperatures of the warm surface and of the room give the exergy demand of the heater surface and of the room. The air temperature of the room, θ_r, is assumed to homogeneous. The effects of varying surface and air temperatures, and of radiative and convective heat transfer processes between them, are neglected here. The surface temperature of the heater, $\theta_{h,}$ is estimated as the logarithmic mean temperature (LMT) of the carrier and the room air (equation 22), where ΔT_{LMTD} is the logarithmic mean temperature difference between 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 23; Moran and Shapiro, 1998).

$$\theta_{h,} = \Delta T_{LMTD} + \theta_r \tag{22}$$

$$\Delta T_{LMTD} = \frac{T_{in,ce} - T_{ret,ce}}{\ln\left(\dfrac{T_{in,ce} - T_r}{T_{ret,ce} - T_r}\right)} \tag{23}$$

Equation (24) shows the exergy balance for the room air subsystem. Equations (25) and (26) show the exergy going into and out of the room air, respectively.In equation (27) these are used to calculate the exergy losses occurring during the heat transfer process. They result from the temperature difference between the the heater surface and the room air temperature.

$$Ex_{in,r} - \Delta Ex_r = Ex_{out,r} \tag{24}$$

$$Ex_{in,r} = Ex_{h,b,in} = \Phi_{h,b} \cdot \left(1 - \frac{T_0}{T_h}\right) \tag{25}$$

$$Ex_{out,r} = Ex_{h,b,out} = \Phi_{h,b} \cdot \left(1 - \frac{T_0}{T_r}\right) \tag{26}$$

$$\Delta Ex_r = Ex_{h,b,in} - Ex_{h,b,out} = \Phi_{h,b} \cdot T_0 \cdot \left(\frac{1}{T_r} - \frac{1}{T_h}\right) \tag{27}$$

1.2.3 Emission system

The exergy balance of the emission system is:

$$Ex_{in,ce} = Ex_{ret,ce} + Ex_{ls,ce} + Ex_{h,b,in} + \Delta Ex_{irrev,ce} = Ex_{ret,ce} + Ex_{h,b,in} + \Delta Ex_{ce} \tag{28}$$

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.

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, $\Delta Ex_{irrev,ce}$. In this manner, the total exergy consumption in the emission system, ΔEx_{ce}, can be obtained.

In equations (29) and (30) the expression for the exergy consumption is given. Equation (31) shows the thermal exergy demand of the emission system.

$$\Delta Ex_{ce} = Ex_{ls,ce} + \Delta Ex_{irrev,ce} \tag{29}$$

$$\Delta Ex_{ce} = \frac{\left(\Phi_{in,ce} - \Phi_{ret,ce}\right)}{\left(T_{in,ce} - T_{ret,ce}\right)} \left[\left(T_{in,ce} - T_{ret,ce}\right) - T_0 \cdot \ln\left(\frac{T_{in,ce}}{T_{ret,ce}}\right)\right] - \Phi_{h,b} \cdot \left(1 - \frac{T_0}{T_h}\right) \tag{30}$$

$$\begin{aligned} Ex_{ce} &= Ex_{h,b,in} + \Delta Ex_{ce} = Ex_{in,ce} - Ex_{ret,ce} \\ &= \frac{\left(\Phi_{in,ce} - \Phi_{ret,ce}\right)}{\left(T_{in,ce} - T_{ret,ce}\right)} \cdot \left[\left(T_{in,ce} - T_{ret,ce}\right) - T_0 \cdot \ln\left(\frac{T_{in,ce}}{T_{ret,ce}}\right)\right] \end{aligned} \tag{31}$$

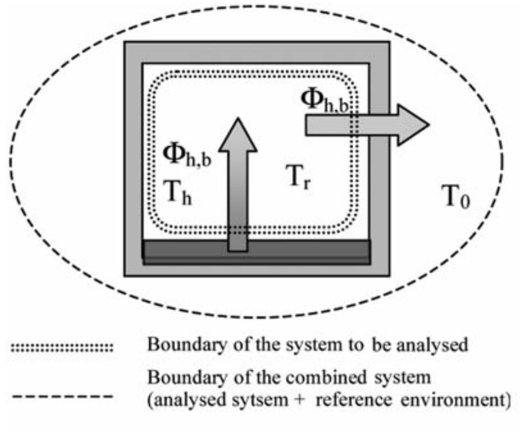


Figure 7: Energy flows, temperature levels and boundaries for the room air subsystem.

1.2.4 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 Excel-based tool for assessment of exergy flows in buildings. 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, ΔT_d.

Similarly as for the emission subsystem, the exergy demand (32) and exergy consumption (33) are also defined.

$$\mathrm{Ex}_d - \Delta\mathrm{Ex}_d = \mathrm{Ex}_{ce} = \mathrm{Ex}_{in,d} - \mathrm{Ex}_{ret,d} \qquad (32)$$

$$\Delta\mathrm{Ex}_d = \frac{\left(\Phi_{ls,d}\right)}{\left(\Delta T_d\right)}\left[\Delta T_d - T_0 \cdot \ln\left(\frac{T_d}{T_d - \Delta T_d}\right)\right] \qquad (33)$$

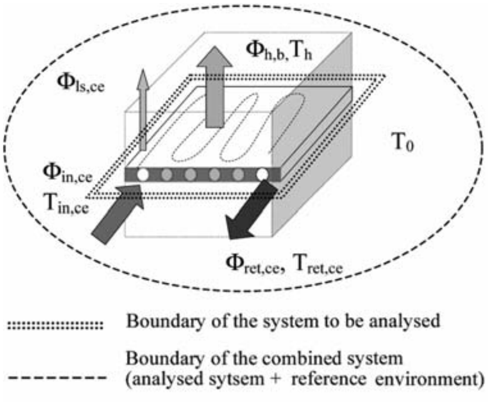


Figure 8: Energy flows, temperature levels and boundaries for the emission subsystem. .

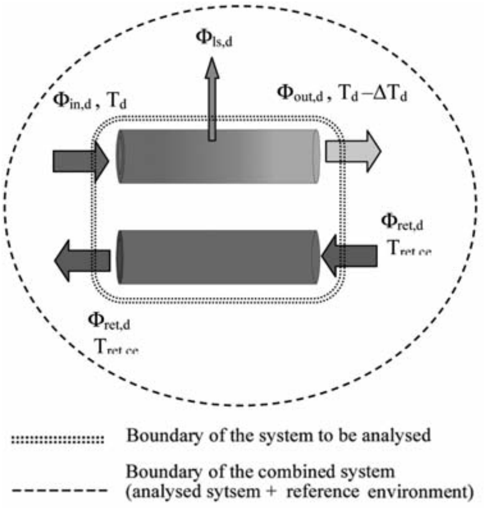


Figure 9: Energy flows, temperature levels and boundaries for the distribution subsystem.

1.2.5 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:

$$\sum \mathrm{Ex}_{in,s} - \Delta\mathrm{Ex}_{irrev,s} = \sum \mathrm{Ex}_{out,s} + \mathrm{Ex}_{ls,s} + \mathrm{Ex}_{sto} \qquad (34)$$

Where the sums are over all inputs and outputs resuting 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.

$$\mathrm{Ex}_{ch,s} = \mathrm{Ex}_{disch,s} + \mathrm{Ex}_{ls,s} + \Delta\mathrm{Ex}_{irrev,s} + \mathrm{Ex}_{sto,s} \qquad (35)$$

$$\mathrm{Ex}_{ch,s} = \frac{\left(\Phi_{ch,s}\right)}{\left(T_{ch,in} - T_{ch,ret}\right)}\left[\left(T_{ch,in} - T_{ch,ret}\right) - T_0 \cdot \ln\left(\frac{T_{ch,in}}{T_{ch,ret}}\right)\right] \qquad (36)$$

$$\mathrm{Ex}_{disch,s} = \frac{\left(\Phi_{disch,s}\right)}{\left(T_{disch,ret} - T_{disch,in}\right)}\left[\left(T_{disch,ret} - T_{disch,in}\right) - T_0 \cdot \ln\left(\frac{T_{disch,ret}}{T_{disch,in}}\right)\right] \qquad (37)$$

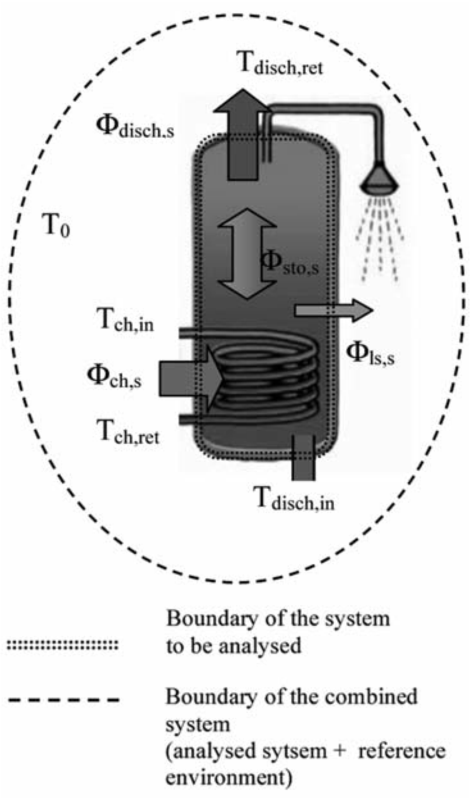


Figure 10: Energy flows, temperature levels and boundaries for the storage subsystem.

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 accout the time dependence of the variables involved (e.g. dT/dt).

For a given storage tank with n layers of storage fluid, the exergy of the heat losses and stored energy can be written as shown in equations (38) to (40). The exergy loss and 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.

$$Ex_{ls,s} = \sum_{i=1}^{i=n} \frac{\left(\Phi_{i,ls,s}\right)}{\left(T_{i,s}\big|_t - T_{i,s}\big|_{t+1}\right)} \left[\left(T_{i,s}\big|_t - T_{i,s}\big|_{t+1}\right) - T_0 \cdot \ln\left(\frac{T_{i,s}\big|_t}{T_{i,s}\big|_{t+1}}\right)\right] \quad (38)$$

With

$$T_{i,s}\big|_t - T_{i,s}\big|_{t+1} = \frac{dT}{dt} \quad (39)$$

$$Ex_{sto,s} = \sum_{i=1}^{i=n} \frac{\left(\Phi_{i,sto,s}\right)}{\left(T_{i,s}\big|_{t+1} - T_{i,s}\big|_t\right)} \left[\left(T_{i,s}\big|_{t+1} - T_{i,s}\big|_t\right) - T_0 \cdot \ln\left(\frac{T_{i,s}\big|_{t+1}}{T_{i,s}\big|_t}\right)\right] \quad (40)$$

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

$$\Delta Ex_{irrev,s} = Ex_{ch,s} - Ex_{disch,s} - Ex_{ls,s} - Ex_{sto,s} \quad (41)$$

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.

$$\Delta Ex_s = \Delta Ex_{irrev,s} + Ex_{ls,s} \quad (42)$$

1.2.6 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 other 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.

1.2.6.1 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:

$$\Delta Ex_g = Ex_g - Ex_{ch,s} \quad (43)$$

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

$$Ex_g = \Phi_g \cdot F_{q,g} \quad (44)$$

1.2.6.2 Ventilation system

Figure 11 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.

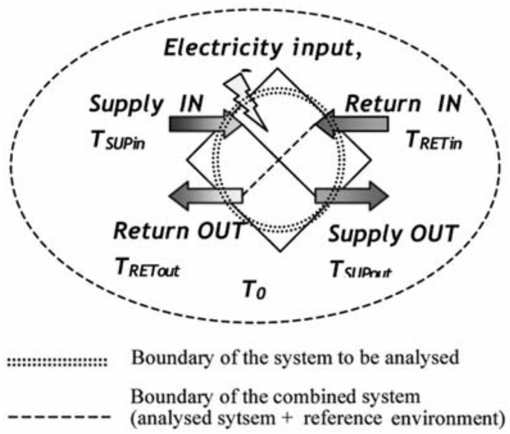


Figure 11: Energy flows, temperature levels and boundaries for a ventilation unit.

$$Ex_{v,aux} + Ex_{SUPin} + Ex_{RETin} - \Delta Ex_v = Ex_{SUPout} + Ex_{RETout} \qquad (45)$$

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

$$\begin{aligned}\Delta Ex_v &= Ex_{v,aux} + Ex_{RET} - Ex_{SUP} \\ &= Ex_{v,aux} + \overbrace{Ex_{SUPin} - Ex_{SUPout}}^{-Ex_{SUP}} + \overbrace{Ex_{RETin} - Ex_{RETout}}^{Ex_{RET}}\end{aligned} \qquad (46)$$

In equations (45) and (46) 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 is higher than the exergy content of this airflow at the inlet. The negative sign indicates, therefore, that no exergy is provided to the supply airflow; instead, it is receiving it from the exhaust airflow.

Each of the terms in equation (46) can be calculated as follows:

$$Ex_{v,aux} = P_{v,aux} \cdot F_{q,el} \qquad (47)$$

$$\begin{aligned}Ex_{SUP} &= Ex_{SUPout} - Ex_{SUPin} \\ &= \frac{\Phi_{SUP}}{(T_{SUPout} - T_{SUPin})} \cdot \left((T_{SUPout} - T_{SUPin}) - T_0 \cdot \ln\left(\frac{T_{SUPout}}{T_{SUPin}}\right)\right)\end{aligned} \qquad (48)$$

$$\begin{aligned}Ex_{RET} &= Ex_{RETin} - Ex_{RETout} \\ &= \frac{\Phi_{RET}}{(T_{RETin} - T_{RETout})} \cdot \left((T_{RETin} - T_{RETout}) - T_0 \cdot \ln\left(\frac{T_{RETin}}{T_{RETout}}\right)\right)\end{aligned} \qquad (49)$$

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

$$Ex_v = Ex_{in} - Ex_{out} = Ex_{SUP} + \Delta Ex_v \qquad (50)$$

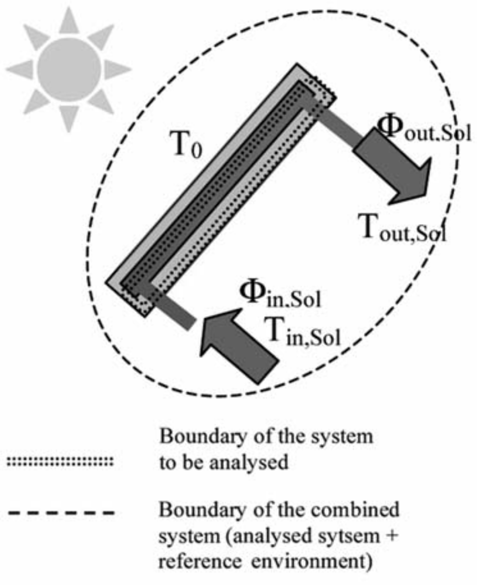


Figure 12: Energy flows, temperature levels and boundaries for a solar thermal collector.

1.2.6.3 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. At the same time, the earth emits 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.

Following this approach, low temperature heat obtained as output from the solar collectors is regarded as input for the storage system.

$$Ex_{coll} = \frac{(\Phi_{out,sol} - \Phi_{in,sol})}{(T_{out,sol} - T_{in,sol})} \cdot \left[(T_{out,sol} - T_{in,sol}) - T_0 \cdot \ln\left(\frac{T_{out,sol}}{T_{in,sol}} \right) \right] \qquad (51)$$

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 1.2.5.

$$\Delta Ex_{coll} = Ex_{ls,d,coll} \qquad (52)$$

---

[1] The quality of an energy flow is depicted by the entropy associated to it. The exergy concept combines, therefore, regards on the quantity (1st law of thermodynamics) and quality (entropy, 2nd law of thermodynamics) associated to it.

[2] The case study and results presented in this section are part of the paper by Sakulpipatsin, van der Kooi, Itard and Boelman, Selection of a Reference Environment for the Calculation of the Exergy Value of Indoor Air in Buildings, published in the 3rd International Energy, Exergy and Environment Symposium (IEEES) held on 2006 at the University of Èvora, Portugal (Sakulpipatsin et al., 2006)

[3] The calculation method presented here is based on that derived by Schmidt, Design of Low Exergy Buildings – Method and Pre-Design Tool. The international Journal of Low Energy and Sustainable Buildings, (2004) Vol. 3, pp.1-47 (Schmidt, 2004).

2 PARAMETERS FOR CHARACTERISING EXERGY PERFORMANCE

2.1 Exergy efficiencies

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).

However, several different definitions of exergy efficiency parameters can be found in the literature. At least two types of exergy efficiencies can be identified and differentiated: "simple" or "universal" and "rational" or "functional" (Cornelissen, 1997; Tsatsaronis, 1993). Their mathematical expressions are shown in equations (53) and (54).

2.1.1 Simple exergy efficiency

The simple exergy efficiency is an unambiguous definition for the exergy performance of a system. However, it works better when all the components of the incoming exergy flow are transformed into some kind of useful output (Cornelissen, 1997). In most of building systems this is not the case, since some part of the exergy input is fed back again to the energy system. For example, in an water-based heat or cold emission system in a building, outlet water flows back via return pipes into the heat/cold generation system and, thus, does not constitute a useful output. The simple efficiency gives a figure on how close a process is to ideal performance (Torío et al., 2009).

$$\Psi_{simple} = \frac{Ex_{out}}{Ex_{in}} \qquad (53)$$

2.1.2 Rational exergy efficiency

The rational exergy efficiency, in turn, accounts for this difference between "desired output" and any other kind of outflow from the system. Therefore, it is a more accurate definition of the performance of a system. In consequence, it can be better used without leading to false conclusions. 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 (Torío et al., 2009).

$$\Psi_{rat} = \frac{Ex_{des,out}}{Ex_{in}} \qquad (54)$$

2.1.3 Example[4]

To further illustrate the difference between both efficiency definitions, an example based on operational data for an air handling unit (AHU) from (Marletta, 2008) for cooling, dehumidification and re-heating of supply air is used (see Figure 13). Properties from state E are used to define the reference environment (outdoor air, see Table 7 and Figure 13). Water inlet temperatures of 8 and 60°C and temperature drops of 5 and 10°C are regarded for the cooling and heating coils respectively. An air flow of 1kg/s is supplied by the unit (points A, E, I, and R in Figure13). Heating and cooling coils are considered adiabatic heat exchangers and resulting mass flows for the heating and cooling coils are 2.51 kg/s and 0.126 kg/s respectively (points 1, 2, 3, and 4 in Figure 13). Equations (55) and (56) show the analytical expression for the simple and rational efficiencies applied to this particular example.

$$\begin{aligned}\Psi_{simple} &= \frac{Ex_{out}}{Ex_{in}} \\ &= \frac{\dot{m}_a \cdot ex_I + \dot{m}_{cw} \cdot ex_{cw} + \dot{m}_{cc} \cdot ex_2 + \dot{m}_{hc} \cdot ex_4}{\dot{m}_a \cdot ex_E + \dot{m}_{cc} \cdot ex_1 + \dot{m}_{hc} \cdot ex_3} \\ &= 0.985\end{aligned} \qquad (55)$$

$$\begin{aligned}\Psi_{rat} &= \frac{Ex_{des,out}}{Ex_{in}} \\ &= \frac{\dot{m}_a \cdot \left(ex_I - ex_E\right)}{\dot{m}_{cc} \cdot \left(ex_1 - ex_2\right) + \dot{m}_{hc} \cdot \left(ex_3 - ex_4\right)} = 0.216\end{aligned} \qquad (56)$$

Table 7: Temperature, water content, enthalpy and exergy regarded for each of the working conditions in the schema of the AHU in Figure 13 (Marletta, 2008)

	T [°C]	ω [g/kg]	h [kJ/kg]	ex [kJ/kg]
A	26	10.5	55.76	0.61
E	35	21.4	89.90	0.00
I	18.5	9.5	45.28	1.05
R	13.3	9.5	37.29	1.40
1	8	-	-	77.83
2	13	-	-	76.02
3	60	-	-	76.60
4	50	-	-	74.05
C	-	-	-	75.92

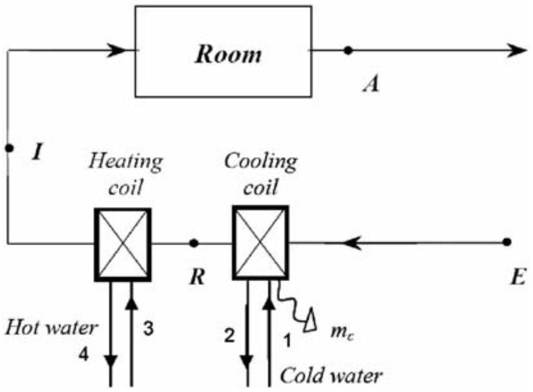


Figure 13: Schema of an air handling unit (AHU) for cooling, dehumidification and re-heating of supply air (Marletta, 2008) modified.

In the example the large difference between the simple and rational exergy efficiencies is evident. If all exergy input would be used to provide a given output they would become equivalent. However, as long as some processes are not strictly desired output from the system, mismatching between them arises as rational exergy efficiency accounts for exergy losses in the form of undesired output (in addition to those derived from non-ideal performance or irreversible processes). Water condensate, m_{cw} in Figure 13, which could be re-used in the process thus lowering exergy losses from dehumidification process, leaves the system and is not reused to produce any desirable output, being responsible for the low values of the rational exergy efficiency as compared to the simple one. Thus, rational exergy efficiencies are more suitable to pinpoint best use and optimization possibilities of an energy system.

All exergy efficiencies given in this report will be, thus, be "rational" exergy efficiencies.

2.2 Overall exergy efficiency

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 5 is given in equations (57) and (58). Overall efficiencies are derived from an input/output approach 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).

$$\Psi_{\text{single},r} = \frac{Ex_{in,env}}{Ex_{in,r}} \qquad (57)$$

$$\Psi_{ove} = \frac{Ex_{out,env}}{Ex_{in,prim}} \qquad (58)$$

2.3 Exergy expenditure figure

Schmidt, Torío and Sager (2007) define the "exergy expenditure figure" for characterising the exergy supply in buildings. In equation (58) the exergy expenditure figure is defined for a component i of an energy system. It is calculated as the ratio of the exergy input (effort) required to supply a given energy demand and the energy demand itself (use). Therefore, it represents a quality factor (exergy to energy ratio) of the energy processes occurring in the given component.

$$\varepsilon_i = \frac{Effort}{Use} = \frac{Ex_{in,i}}{En_{out,i}} = \frac{F_{q,in,i}}{\eta_i} \qquad (59)$$

Figure 14 shows the energy and exergy flows used for the general definition of the exergy expenditure figure for a component *i*.

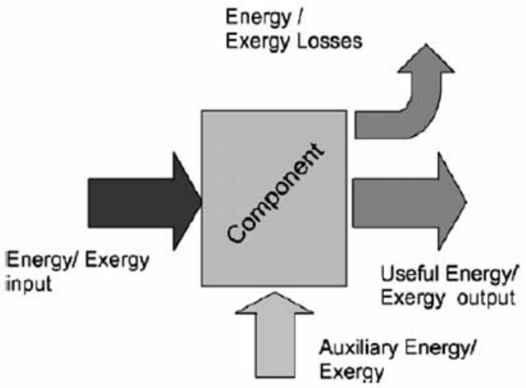


Figure 14: Graphical representation of the exergy flows included in the exergy expenditure figure for a general component of an energy system (Schmidt et al., 2007).

Energy and exergy losses happening in the component are implicitly taken into account by the ratio of provided output to required input. 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 (59)).

The exergy expenditure figure needs to be compared to the exergy to energy ratio of the energy demand to be provided, i.e. to the quality factor of the energy demand. If the values are close this indicates a good matching between quality levels (i.e. exergy) of the energy supplied and demanded. In turn, a mismatch indicates bad matching and, in consequence, suggest that other energy sources should be used to provide that specific use and/or energy losses need to be reduced.

For the particular application of space heating and cooling of buildings, the quality factors (or exergy to energy ratio) of the energy demanded are very low. Figure 15 shows that for space heating applications and reference and indoor air temperatures of 0°C and 20°C respectively, the quality factor of energy demand is 7%. Therefore, for space heating (and cooling) of buildings, the closer the exergy expenditure figure for a given system to 7%, the better the system exergy performance is. Consequently, in space heating and cooling applications, lower exergy expenditure figures indicate more optimised energy supply systems.

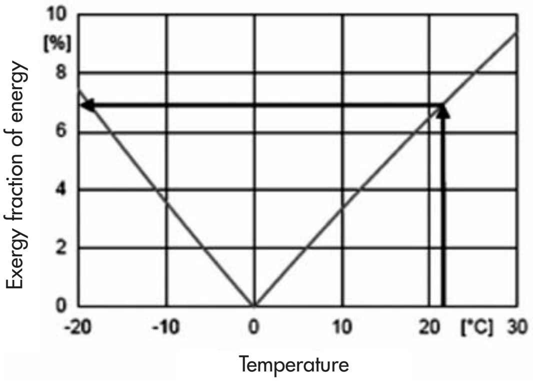


Figure 15: For a reference temperature of 0°C, the exergy content of the energy in the room air, assuming an indoor air temperature of 21°C, is 7%.

2.3.1 Case study[5]

For the following considerations, a building from the IWU study (IWU 2003) – a single-family dwelling, built between 1995 and 2000 – has been chosen as an example. For this home, an indoor air temperature of 21°C is assumed as the reference temperature, and the ambient air temperature during a typical winter day is 0°C. The specific heat transmission coefficient of the building envelope H'_T, a measure for the insulation standard of the building, is 0.44 W/m^{2}K. The building is to be ventilated via windows and natural forces, and a mean air exchange rate of 0.6 ACH has been assumed. Domestic hot water is heated electrically and demand is assumed to be 45 l/(pers*d) with 2.5 persons present as a mean value.

For the building service equipment and the heating system of the building, six different cases have been studied intensively:

1) A condensing boiler and standard radiators with the temperature levels for supply and return of 55/45°C as emission system.
2) A condensing boiler and a floor heating system with temperature levels for supply and return of 28/22°C.
3) A biomass-fired boiler (e.g. wooden pellet burner) and a floor heating system with temperature levels for supply and return of 28/22°C.
4) A condensing boiler and a solar thermal system, covering 40% of the heating load as a secondary heat source. and a floor heating with temperature levels for supply and return of 28/22°C.
5) A ground source heat pump with a ground heat exchanger and a floor heating systems with temperature levels for supply and return of 28/22°C.
6) A district heating connection, which is fired with a fossil fuel, and a floor heating systems with temperature levels for supply and return of 28/22°C

2.3.1.1 Results

A common energetic assessment of the building, conducted here under steady state conditions, is shown in Figure 16. Because of the different primary energy factors of the fuel sources the fossil part of the energy supply varies between cases even though the total energy use is about the same. Variations are caused by varying efficiencies of the building service systems.

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

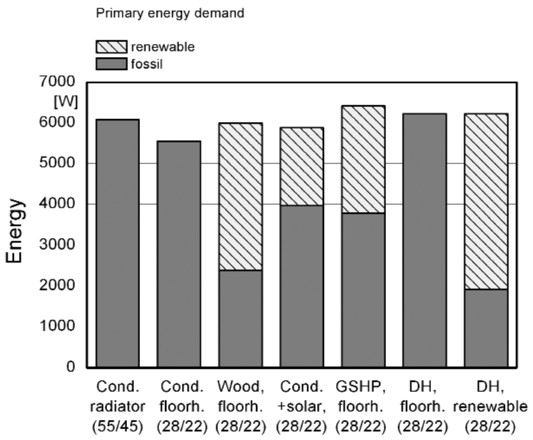


Figure 16: Primary energy demand (fossil and renewable) for six different energy supply systems (steady state calculation).

A comparison of an energetic and exergetic assessment of the primary energy demand from fossil and renewable sources is shown in Figure 17. The six different building service system configurations use varying amounts of exergy to meet the heating requirement. Especially the systems that only have a condensing boiler or wood pellet burner utilises about 100% exergy for that task. Systems using the district heating supply are able meet the heating requirement with less than half the exergy.

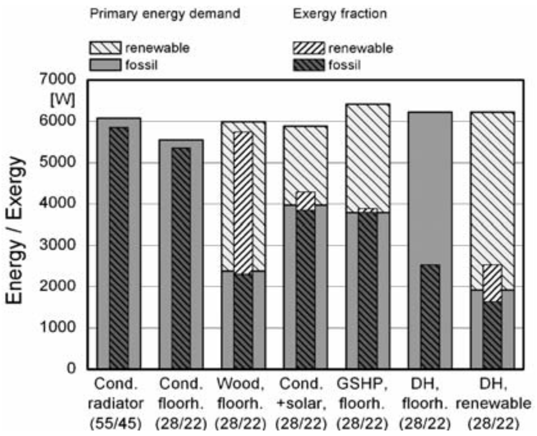


Figure 17: Primary energy demand (fossil and renewable) for six different energy supply systems and the related exergy (steady state calculation).

Exergetic assessments of heating systems facilitate comparisons of performance and allow to assess the efficient use of different energy sources based on thermodynamic principles, independent of political considerations and national borders. This includes the assessment of potentials of renewable energy sources. It is concluded that a rational use of energy has to be assessed with an additional exergy analysis and that exergy use should be limited, as it is done today with primary energy. To achieve this the entire building should be regarded as one system (Schmidt et al., 2007).

2.3.1.2 The „exergy expenditure figure" as a benchmark

A component, e.g. a radiator, is designed to supply a specified heating power. It should heat the room with a certain amount of heat, which is to be delivered to the room space. Energy is transmitted and used within the space, and heat has been exchanged from the heat carrier water to the air within the room. A component should perform this task with the smallest possible amount of exergy. Furthermore, the use of high quality (auxiliary) energy, e.g. electrical power, and losses to the environment,should be low.

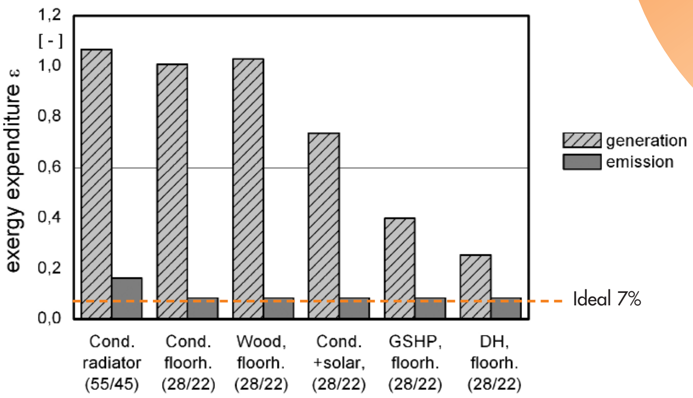


Figure 18: Assessment of the components "heat generation" and "emission system" with the exergy expenditure figure for the chosen variants of the building service system.

As described above, the exergy fraction of the energy needed to heat a room is only 7%. This value can be directly compared to the exergy expenditure figures of the building service systems discussed above (Figure 18). They satisfy the heat demand with a more or less well-adapted heat supply. 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, heating the same room the radiator system uses more exergy than the floor heating system, which is closer to ideal in terms of exergy use.

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.

2.4 Benchmarking proposal

Favrat et al. (2008) present a discussion and description of some of the exergy efficiencies and exergy-based parameters included in the new energy regulation for the Swiss canton of Geneva. The overall rational exergy efficiency (see section 2.2) is one of several parameters chosen for characterizing the buildings performance. Heating, cooling and lighting in buildings are the main services regulated in the new energy code.

In the Swiss energy regulation presented in (Favrat et al., 2008) the energy supply chain for buildings is divided into four subsystems: room convector, building plant, district heating or cooling plant and power plant. In addition to the overall chain exergy efficiency, single exergy efficiencies for each of the four subsystems are also given.

Schmidt et al. (2007) developed a benchmarking proposal for characterising the performance of energy building systems. The authors define the so-called "exergy expenditure figure", presented in the previous section, for characterising the exergy supply in buildings. The benchmarking proposal is based on the combined limitation of the primary energy (fossil) use of the building and the new parameter called "exergy expenditure figure".

2.4.1 Example[6]

In order to show the different behaviour and order of magnitude of the two main exergy indicators defined in both approaches (exergy efficiency and exergy expenditure figures) their values for four different examples of building systems are listed in Table 8.
Equations (60) and (61) are used for the calculation of the exergy expenditure figures for the boiler and emission systems respectively. The reference temperature is regarded as 0°C in all cases.

$$\varepsilon_{boil} = \frac{Ex_{in,boil}}{En_{out,boil}} = \frac{F_{q,fuel}}{\eta_{boil}} \qquad (60)$$

$$\varepsilon_{ce} = \frac{Ex_{in,ce}}{En_{out}} = \frac{1}{\eta_{ce} \cdot \left(T_{in} - T_{ret}\right)} \left[\left(T_{in} - T_{ret}\right) - T_0 \ln \frac{T_{in}}{T_{ret}}\right] \qquad (61)$$

For space heating and cooling applications, the lower the exergy expenditure figure ε (i.e. the closer it is to the quality factor of energy demanded 7% as shown in Figure 15) the better the system performs. On the contrary, higher exergy efficiency of the system, Ψ_{single}, indicates a better system performance.

Both parameters would lead to similar conclusions regarding the performance of the emission systems (see Table 8). Due to the lower temperature levels of the energy supplied (lower inlet and return temperatures) as compared to the temperature level of the energy demanded (room air, e.g. 20°C), floor heating systems allow reducing the exergy losses on the energy transfer to the room air, thus having a better exergy performance.

However, it is important to note that the exergy efficiency is a more sensitive parameter than the exergy expenditure figure for evaluating the performance of a boiler coupled with different energy supply systems (e.g. emission systems with different inlet and return temperature levels). In the exergy efficiency both the quality levels of the energy supplied and demanded are regarded, i.e. lowering down the supply temperature levels leads to a reduction of the exergy supplied. The exergy efficiency is suitable for checking the performance of each component in the energy system separately, but does not give insight on the suitability of each component for providing the final energy demand.

In contrast for the exergy expenditure figure only the quality level of the energy supplied (effort) is regarded, whereas the output (use) is regarded in energy terms. Therefore, as long as a certain energy source with its corresponding quality level is used with the same energy efficiency, the exergy expenditure figu-

Table 8: Numerical values for the single exergy efficiency as defined in (Favrat et al., 2008) and exergy expenditure figure as defined in (Schmidt et al., 2007) for four examples of building systems. Values for the exergy efficiencies are directly taken from (Favrat et al., 2008); exergy expenditure figures have been taken from (Torío et al., 2009).

		Generation system		Emission system	
Parameter	Reference	Condensing boiler (65/55°C)	Condensing boiler (45/35°C)	Convectors (65/55°C)	Floor heating (45/35°C)
Ψsingle [-]	Favrat et al., 2008	0.16	0.12	0.38	0.53
ε [-]	Schmidt et al. 2008	1.03	1.03	0.19	0.13
η [-]		0.92	0.92	0.95	0.95

re 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 componen and the final energy demand, i.e. of the suitability or appropriateness of the energy system for providing a given use.

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[4] The case study and results presented in this section are part of a paper by Torío, Angelotti, and Schmidt, Exergy analysis of renewable energy-based climatisation systems for buildings: A critical view. Energy and Buildings 41 (2009) pp. 248-271. (Torío et al., 2009).

[5] The example and results presented in this section are part of a paper by Schmidt, Benchmarking of "LowEx" buildings. In: Proceedings of the Nordic Symposium of Building Physics 2008, Copenhaguen (Denmark). (Schmidt, 2008)

[6] The case study and results presented in this section are part of a paper by Torío, Angelotti, and Schmidt, Exergy analysis of renewable energy-based climatisation systems for buildings: A critical view. Energy and Buildings 41 (2009) pp. 248-271. (Torío et al., 2009)..

3 REVIEW ON THE USE OF EXERGY ANALYSIS FOR BUILDING SYSTEMS[7]

In recent years several authors have applied the exergy concept to the analysis and optimization of building systems. Extensive scientific literature can be found on the topic. However, different frameworks for exergy analysis have been used: Most studies use steady-state exergy analysis while some authors perform dynamic analysis. The study boundaries and limits of the systems under investigation also differ significantly.

Yet, in order to determine the state of the art of exergy analysis of building energy systems a review of the literature is needed. Results from the different analyses can be brought together and common conclusions regarding this thermodynamic assessment of building energy systems can be drawn. Strengths, weaknesses and future research required can be identified. This literature review can be found in (Torío et al., 2009).

3.1 Heating systems

3.1.1 Solar thermal systems

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

For exergy analysis of solar thermal systems, two different frameworks can be found in the literature:

- the conversion of solar radiation into low temperature heat is included in the analysis and solar radiation is the first exergy input into the system (Bejan, 1982; Gunherhan and Hepbasli, 2007);
- heat output of the solar collector field is evaluated as the given output of the system and the conversion of solar radiation into low temperature heat is disregarded in exergy terms (Torío and Schmidt, 2008; Meir, 2002; Sandnes, 2003).

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

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

3.1.2 Ground-coupled heat pumps

For the exergy analysis of heat pumps the boundary and framework chosen also significanty influence the results obtained. Again, a uniform framework for exergy analysis of these systems could not be found (Torío et al., 2009). (Hepbasli and Akdemir, 2004) and (Akpinar and Hepbasli, 2007) regard only electricity as energy or exergy input into the heat pump, disregarding the exergy of energy flow from the ground. Ozgener and Hepbasli (2007), Esen et al. (2007) and Hepbasli and Tolga-Balta (2007), include the exergy flow from the ground as input into the heat pump for assessing its exergy efficiency. Ozgener and Hepbasli (2007), Esen et al. (2007) and Hepbasli and Tolga-Balta (2007) regard the exergy demand of the emission system at its temperature level as final demand. Hepbasli and Akdemir (2004) regard the final demand as the energy required by the room or building. The reference temperature chosen differs also significantly depending on the authors: The reference temperature chosen also differs significantly among authors: Hepbasli and Akdemir (2004) consider it as 25°C; Ozgener and Hepbasli (2007) take the design heating temperature of the site, and Hepbasli and Tolga-Balta (2007) considers the average outdoor temperature of the site during the monitoring of the system.

As a consequence estimates of overall exergy efficiencies for heat pump units vary greatly: from almost 3% to 80% (this variation is markedly greater than that of the corresponding energy performance figures regarded: COP varies from 1.65 to 2.80). The component identified to have the greatest potential for improvement within the heat pump cycle (i.e. compressor, condenser, evaporator and expansion valve) is also dependent on the boundary Since the exergy efficiency of a heat pump strongly decreases as the reference temperature increases, steady-state reference conditions chosen in each study are expected to strongly influence the results of the exergy analysis, making comparisons between studies extremely difficult.

This once again highlights the importance of establishing a common framework and uniform method for exergy analysis of building systems.

3.1.3 Solar assisted heat pumps

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

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

3.1.4 Biomass boilers

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

Wood is a highly valuable energy source, i.e. with high exergy content. Exergy analysis regards the quality of energy sources, but not its renewability or CO_2 neutrality. Thus, when it is used in low temperature (i.e. low exergy) applications it comes with high exergy losses, representing a non-optimal solution. Indeed, the overall exergy performance of a wood-pellets boiler, for instance, is very similar to that of a condensing boiler: 5.53 and 5.9% respectively.

Results from energy and exergy analysis for wood-boilers are contradictory: from a fossil primary energy perspective wood would always be advisable (because of its CO_2 neutrality); on the other hand, its exergy efficiency is just as low as that of a conventional boiler, and lower than that of low-exergy systems such as solar thermal units or ground-source heat pumps (7.4%).

In this case, exergy analysis would help identifying space heating by direct burning of wood as an inefficient energy supply system. It leads to conclude that wood, as high quality energy source, should rather be used for high quality uses, such as electricity production or combined heat and power production (CHP units).

3.2 Cooling systems

3.2.1 Thermally driven compression cycles

Several authors have used exergy analysis to improve the performance and operation of thermally driven compression machines for cooling applications (Pons et al., 1999; Boer et al., 2007; Khaliq and Kumar, 2007; Morosuk and Tsatsaronis, 2008; Sencan et al., 2005) The main conclusion from these studies is that the generator and absorber are the components of the cooling cycle where high irreversibilities arise and, thus, where optimization efforts should first be focused. However, holistic and detailed analysis performed on the whole cycle (i.e. including all components and their interrelationship) (Boer et al., 2007; Morosuk and Tsatsaronis, 2008) shows the strong interdependence of the irreversibilities of the different components. Thus, if the performance of the whole cycle is the target, overall exergy consumption instead of irreversibilities in only one specific component (even that with the greatest exergy consumption) should be minimised.

Furthermore, reducing the generation temperature leads to higher exergy efficiency of the system, despite lowering their energy performance (Sencan et al., 2005; Pons, 1999).

Most studies found focus on the analysis of the absorption cycles as a component of the energy supply chain for a fixed demand. However, analysis of the whole energy chain is required in order to ensure that control strategies proposed lead to an optimised use of the energy flows in building cooling applications.

3.2.2 Desiccant cooling systems

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

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

3.3 General conclusions

From the above statements the following general conclusions about exergy analysis in building systems can be drawn:

- A common framework for exergy analysis of building systems is lacking. Efforts should be made to elaborate a uniform framework for exergy analysis. Furthermore, boundaries and energy processes regarded always should be clearly stated, for they dramatically influence results and conclusions of exergy analysis.
- A methodology for combining and applying conclusions from energy and exergy analysis to building systems in case of contradictory assessment by the two should be worked out. This would help clarifying the benefits and scope of exergy analysis to the wider public.

The scientific work within IEA ECBCS Annex 49 aims at deriving a common analysis framework and method for exergy analysis within the built environment, thus addressing the gaps and problems highlighted above. In the final report a compendium and detailed description of this framework will be included. This framework will intend to provide easy access to the fundamentals of thermodynamics (temperature, heat, pressure, energy, entropy, environmental temperature and exergy).

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[7] The case study and results presented in this section are part of a paper by Torío, H., Angelotti, A. and Schmidt, D. 2008. Exergy analysis of renewable energy-based climatisation systems for buildings: A critical view. Energy and Buildings 41 (2009) pp. 248-271.

4 INNOVATIVE BUILDING CASE STUDIES

Along with a better exploitation of all the energy sources, the use of renewable energy sources is generally acknowledged as another feasible way for sustainability in buildings. However, the systematic exploitation of renewable sources has to cope with limitations that raise the costs of these solutions: most prominent are the specific power and the availability of energy, often making the use of a storage system necessary.

In the present report, 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. Three of them are related to air-conditioning systems with the goal to reduce both the energy required for cooling and for air circulation. The need for cooling, in fact, is steadily increasing in buildings and since there are fewer alternatives for producing cold than for heat generation – cold is commonly produced with air heat pumps with relatively poor efficiency –,using natural ventilation or evaporative cooling would be beneficial.

Two case studies are about seasonal storage systems for both, cooling and heating. Storage systems are necessary for an effective exploitation of renewable energy sources but they are also useful to smooth out peaks in supply and to shift energy generation to times when conditions are optimal. By decoupling demand and supply they pave the way for a flexible energy management.

The last case study is about a heat recovery system for building waste waters similarly to the heat recovery systems in the AHUs. Rational energy use, of course, would include the recovery of all valuable types of energy.

These are the titles of the case studies presented below:

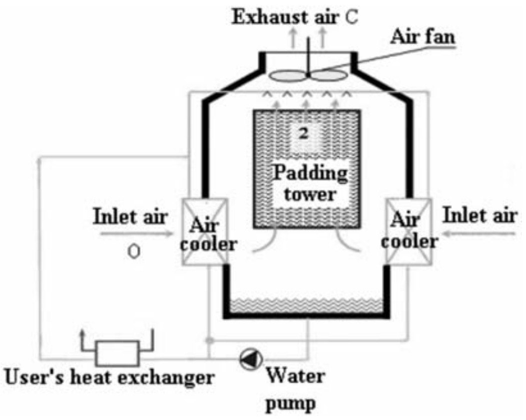
- Innovative Concepts for Exergy Efficient Air-conditioning Systems and Appliances in Buildings
- Temperature and humidity independent control (THIC) air-conditioning system
- Adjustment of the ventilation rates based on the variation in time of the actual needs
- Seasonal heat storage by GSHP system
- Shallow ground heat storage with surface insulation
- Exergy recovery from wastewater in small scale integrated systems

4.1 Innovative Concepts for Exergy Efficient Air-conditioning Systems and Appliances in Buildings[8]

4.1.1 Main features of the concept

By using outdoor dry air as the driving force, the indirect evaporative chiller introduces a novel air-conditioning concept for public buildings in dry regions. It is taking advantage of 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 at 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 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 20 shows, which can use outdoor dry air sufficiently by matching the temperature level of the cold water and the heat sources.



(a) Principle of the chiller.

(b) Picture of the first working unit of the chiller.

Figure 19: Structure of the indirect evaporative chiller.

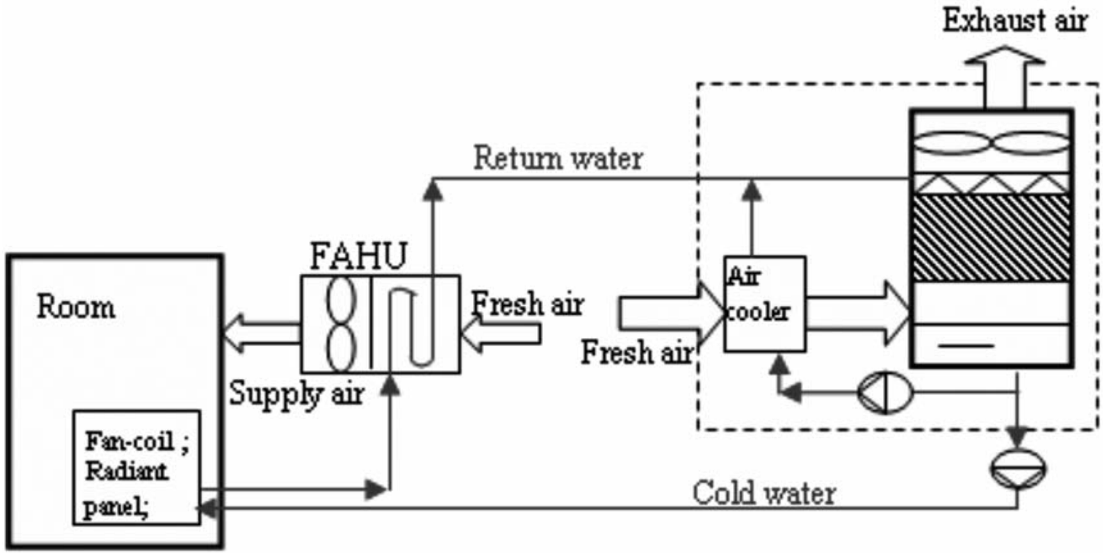


Figure 20: Structure of the air-conditioning system using the indirect evaporative chiller.

4.1.2 Competitiveness

In contrast to common mechanical compression refrigeration systems, the indirect evaporative chiller uses natural, dry outdoor air as a driving force. This way up to 50% of the energy costs can be saved. No CFCs are used, and related pollution is avoided. Compared to common indirect evaporative cooling systems, this chiller uses water as energy carrier instead of air and therefore the power cost for transport of the cooling energy can be significantly reduced. Besides, it produces cold water with the limit temperature being the 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.

4.1.3 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 system, as enough fresh air is supplied into room, a healthier indoor environment can be achieved.

Because of the evaporation water needs to be supplemented with flow rates about 3-5% of the cycle water flow rate. Therefore, this evaporative cooling technology is not suitable for regions where lack of water is a concern. However, for most dry regions in the world this is not a problem.

4.1.4 Performance analysis tools

The structure of the chiller as well as that of the inside sub-components are patented (quasi-counter current air-cooler, counter current padding tower etc.) A simulation model was set up using the EES (Electronic Environmental Simulator) to find the process parameters under different outdoor conditions. Actual devices have been built and deployed in buildings. These test confirmed the feasibility of the concept and allowed to evaluate the performance of the indirect evaporative chiller.

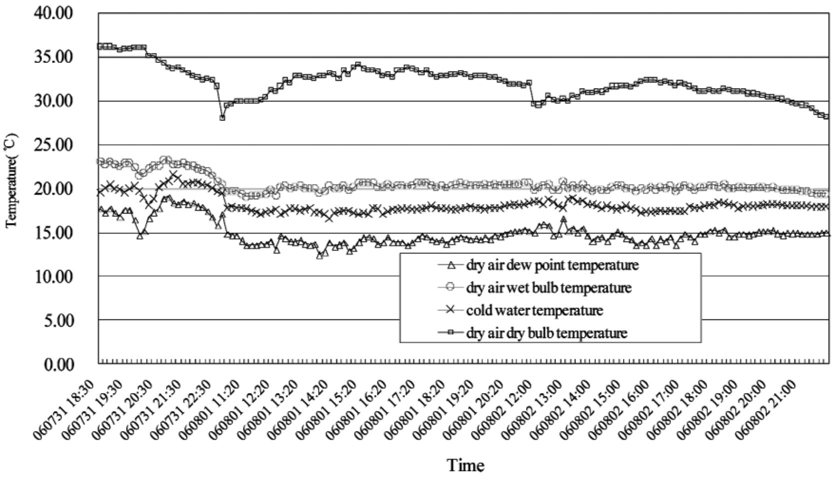


Figure 21: Cold water temperatures compared to dew point and wet bulb temperatures of the inlet air.

4.1.5 Relevance as low-exergy technology

Exergy use in cooling has two big contributions: the exergy needed for heat conversion and the exergy for heat distribution and emission. As for heat conversion, cold water is produced at 16-18 °C, a relatively high temperature suitable for low-exergy cooling; in addition it is produced using dry air as driving force instead of electricity used in common chillers. The use of water also contributes to lowering exergy losses compared to airborne systems, because of a better heat vector behaviour.

4.1.6 Testing performances

The first indirect evaporative chiller was developed in 2005. Performance measurements showed that the outlet water temperature of the chiller is lower than indoor wet bulb and more or less at the middle of the dew point and wet bulb temperatures (Figure 21). The outlet water temperature is mainly influenced by the dew point temperature of the inlet air (Figure 22).

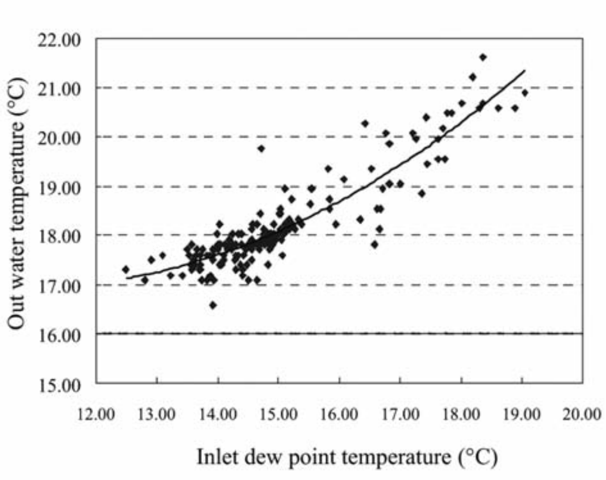


Figure 22: Dependance of water temperature on inlet dew point.

4.1.7 Demonstration projects

From 2005 to now, the dry air driven indirect evaporative chiller and its system have been installed in more than 15 projects serving a building area of about 120,000 m^2. These projects include the Shihezi Kai Rui 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 regions in India and Australia, or parts of 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 et al., 2007a; Tsinghua University, 2008).

4.1.8 Planned further activities

This chiller is operated continuously in the northwest China, not only in Xinjiang Province, but also Gansu and Inner Mongolia. Chances for popularizing this technology in the world are under evaluation.

4.1.9 Internet sites

N/A

Xin Jiang Chinese Medicine Hospital

Shihezi Kai Rui Building

Aksu People´s Hospital

Figure 23: Demo buildings using indrect evaporative chiller.

4.2 Temperature and humidity independent control (THIC) airconditioning system[9]

4.2.1 Main features of the concept

Temperature and humidity control are two main tasks of air-conditioning systems. In most centralized air-conditioning systems in China, the air is cooled at a temperature below the indoor dew point, 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 energy is wasted as a result.

The proposed THIC (Temperature and Humidity Independent Control) system is composed of two separated systems, for temperature and humidity control, respectively (Figure 24). The temperature of the chilled water in the temperature control system is raised from 7°C in conventional systems to about 18°C, which also allows the utilization of natural cooling sources. Even if the chilled water is produced by a mechanical chiller, the COP (Coefficient Of Performance) will be significantly increased.

In the southeast of China, where many large buildings are located, the outdoor air is humid and the main task of air-conditioning systems is to dehumidify the air. Here, dehumidification by liquid desiccant is recommended.

In the northwest of China the outdoor air is dry and the main task of air-conditioning systems is to decrease temperature. Direct or indirect evaporative cooling is recommended.

4.2.2 Competitiveness

(1) Humid area in the southeast of China
The recommend THIC system is composed of a liquid desiccant outdoor air processor to control indoor humidity and a refrigerator with 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 refrigerator.

(2) Dry area in the northwest of China
The recommend 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% of the operating energy can be saved compared to the conventional system.

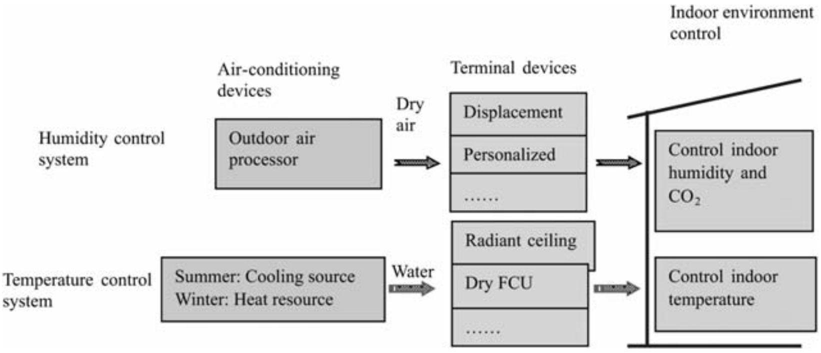


Figure 24: Device scheme.

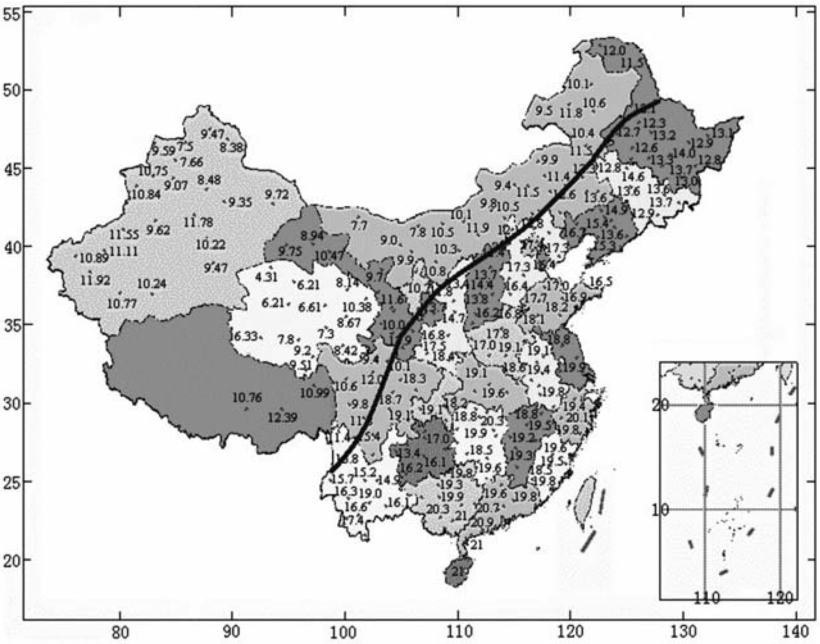


Figure 25: Average humidity ratio of the most humid month. Southeast of the line: outdoor air is humid. Northwest of the line: outdoor air is dry enough.

4.2.3 Side effects

Improved indoor environment: accurate control of indoor humidity as well as indoor temperature. Wet surface are avoided by using the liquid desiccant dehumidification method. An added benefit of the liquid desiccant system is the potential to remove a number of pollutants from the processed air.

4.2.4 Performance analysis tools

A simulation tool based on Matlab was developed and 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).

4.2.5 Relevance as low-exergy technology

This system allows the control of both humidity and temperature by splitting the management of them into two independent systems. Due to a increase in temperature for cooling from 7 °C to 18 °C, a much better performance in terms of exergy can be obtained. With the outside reference environment at 25 °C, the exergy content is 6.4% and 2.4%, respectively, for delivered heat. Similarly a chiller ideally working in the same environment would perform almost 3 times better. As a consequence, relevant exergy amounts can be saved while still ensuring conditions are comfortable in the cooled spaces.

4.2.6 Simulation studies

The performances of various types of liquid desiccant outdoor air processors both in summer and winter, the indirect evaporative chiller, and the THIC system have been simulated. Detailed information can be found in the following references: (Liu et al. 2006; Li et al., 2005; Xie, Jiang, 2008; Xie, Jiang, 2007).

4.2.7 Demonstration projects

From 2005 to the present, over 1,000,000 m^2 of building space in the southeast of China have been equipped with liquid desiccant based THIC system; in the northwest of China over 100,000 m^2 of building space have been equipped with the evaporative cooling based THIC system.

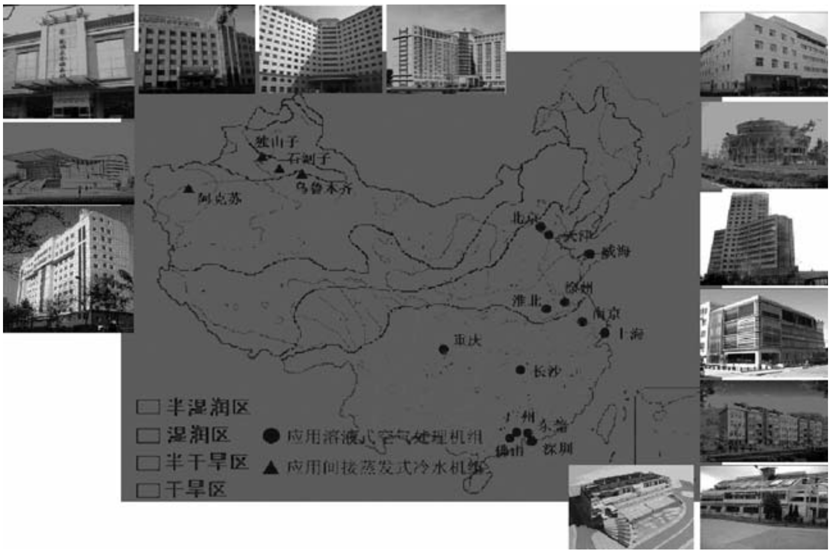


Figure 26: Map of some of the existing buildings using the THIC approach in China.

The detailed monitoring results are presented in the literature (Chen, et al. 2005; Li et al., 2005; Xie, Jiang, 2008; Xie, Jiang, 2007).

4.2.8 Planned further activities

More monitoring building energy use results need to be collected.

4.2.9 Internet sites

N/A

4.3 Adjustment of the ventilation rates based on the variation in time of the actual needs[10]

4.3.1 Main features of the concept

Ventilation plays a key role in overall performance of buildings in terms of energy consumption, indoor air quality and thermal comfort. Ventilation can be accomplished by natural means or by a mechanical system. The uncertainties of controlling airflows and the the –unpredictability of the wind and temperature gradients driving them are the major challenges to the development of purely natural ventilation techniques. Mechanical ventilation on the other hand may result in the unnecessary use of energy. Hybrid technology represents an attempt of combining the benefits of both ventilation strategies in a single 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). This also minimizes the energy required by air conditioning and distribution.

4.3.2 Side effects

Energy required for ventilation represents a large part of the total energy use especially in well insulated buildings. 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 decreasing energy use. Hybrid technology represents a means for achieving both acceptable indoor air quality and good energy performance.

4.3.3 Performance analysis tools

Simulations for a building implementing hybrid ventilation concepts have been performed combining an energy performance model and a ventilation model. The building model has been set up in the TRNSYS environment and as a whole has been schematized as multi-zone system. Airflow calculations within the building have been carried out using CONTAM.

4.3.4 Simulation studies

Studies have been carried out for a medical building. Spaces and related activities are distributed on two floors, which are connected vertically by a large central atrium. The ventilation objective 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, providing a supply of 55 m^3/h of outdoor air per person. Ventilation in each zone varies with its level of occupancy. Winter time operation relies on mechanical ventilation, with the objective of maximizing 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 control airflows entering rooms, patients' spaces are equipped with self regulating hygroscopic vents. These allow airflow depending on the sensed value of relative humidity. If the CO_2 level exceeds the threshold level of 1,000 ppm, mechanical ventilation is turned on. Figure 27 and Figure 28 show the comparison between the results obtained for the hybrid ventilation system (HYBR) and a fully mechanical ventilation strategy run for the entire year (MECH).

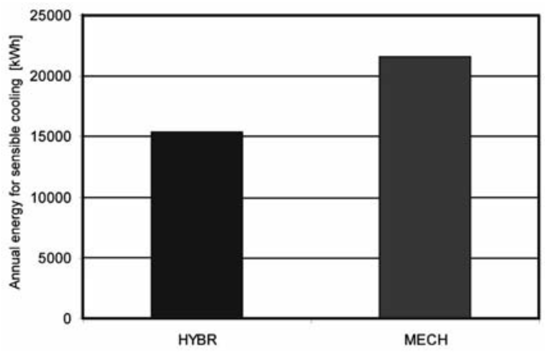


Figure 27: Annual hybrid and mechanic energy use for cooling.

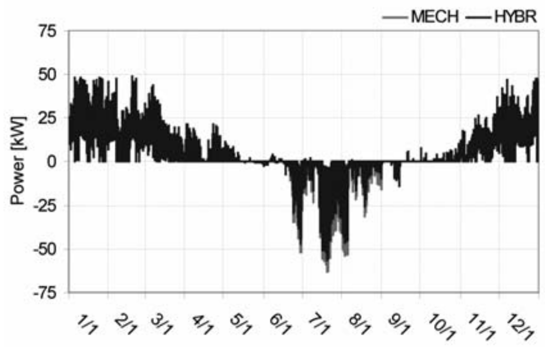


Figure 28: Peak power use.

4.3.5 Relevance as low-exergy technology

Energy use for air circulation in air unit systems is a relevant part of the overall energy balance. To overcome the pressure drops in air ducts, which imply small exergy destruction, electricity-driven fans are needed: their exergetic efficiency is very low. This approach limits the electricity consumption for air circulation by making use of the natural pressure differences in the environment that would be otherwise supplied. Furthermore, active systems, such as chillers, can be switched off to maintain IAQ comfort requirements: as a result in intermediate seasons it is possible to cut off the electricity consumption, that is exergy, and make use of environmental-available sources.

4.3.6 Demonstration projects

N/A

4.3.7 Planned further activities

Research on the benefits of natural ventilation automatic control techniques is 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 controlling airflow rates through self regulating vents or window aerators. Systems will rely on automatic switching between natural and mechanical mode in winter and in periods of poor natural forces or increased demand.

4.3.8 Present evaluation statement (2008-07-09)

Simulations show that it is possible to operate a sustainable low-energy building while still ensuring a comfortable and healthy indoor environment (Villi, de Carli, Ballestrini, 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 1,000 ppm threshold level.

4.3.9 Internet sites

N/A

4.4 Seasonal heat storage with ground source heat pump system[11]

4.4.1 Main features of the concept

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 usually installed far away from each other and utilise the geothermal energy of the constant temperature of far-away soil volumes. This does not allow to use seasonal energy storage. However, in the case of larger buildings where several boreholes have to be installed, a more effective design can be used. The tubes can be installed in a cylindrical pattern. Increasing the number of boreholes decreases the ratio of the cylindrical boundary surface to the heat storage soil volume. As a result, the heat storage soil volume is in contact with a relatively smaller surface of far-away soil volumes. Consequently, the effectiveness of the seasonal heat storage increases. In order to decrease the exergy loss of the stored energy (i.e. decreasing the temperature drop), the heat exchangers are distributed into more groups and used in a suitable sequence during the heating and cooling periods (Simón, 2008).

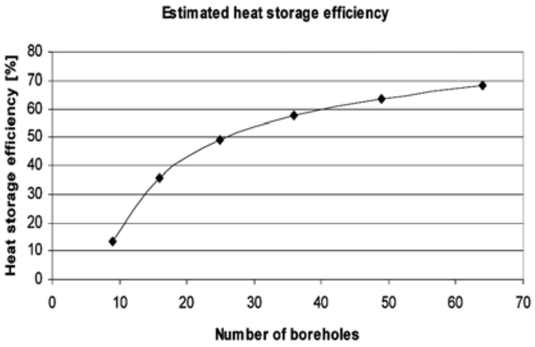


Figure 29: Estimated heat storage efficiency.

4.4.2 Competitiveness

It will also be possible to use the highly exergy efficient GSHP systems 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. The annual consumption of the high-exergy energy carriers, e.g. fossil fuels, can be decreased.

The vertical heat exchangers can be installed relatively close to each other therefore they do not need big ground surface.

4.4.3 Side effects

If the heat is extracted from the soil by an electrically driven heat pump, then, there is no local pollution. For Central European climate conditions, the summer peak of solar energy gain can be utilised. Currently the cost of creating vertical boreholes is very high. Significant solar collector area is needed.

4.4.4 Performance analysis tools

The available simulation programs are Simulink and FlowWent. These programs are not ideally suited for this type of physical problem. Currently we are looking for more suitable tools.

4.4.5 Relevance as low-exergy technology

Many renewable energy sources are not constantly available. Therefore one of the main prerequisites for their exploitation is the ability to store the energy harvested from them. The exploitation of renewable sources should be considered a low-ex approach: Even if solar radiation has a high exergy content, exergy destruction would take place anyway, regardless of human exploitation and its use replaces high-exergy fossil fuels. Seasonal heat storage two positive effects on the exergy consumption in buildings: It allows the massive exploitation of the solar energy in an efficient way and thus freely available exergy is gathered, and it improves the performance of the active, electricity-driven heat pump systems.

4.4.6 Simulation studies

N/A

4.4.7 Demonstration projects

N/A

4.4.8 Monitoring results

Measured data 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. They were covered with thermal insulation, put below the surface and filled with water. The system includes 20 m^2 of 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.

4.4.9 Planned further activities

This is the first year of operation for the heat pump in the experimental building. Therefore there are still no data available covering the entire heating and cooling period.

So far only steady state calculations have been carried out to estimate the performance of system. Dynamic simulations will help to better understand its performance and usability.

4.4.10 Internet sites

N/A

4.5 Shallow ground heat storage with surface insulation[12]

4.5.1 Main features of the concept

The idea presented here is part of an ongoing research project at the Department of Building Physics at KTH (Stockholm, Sweden). By 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 31).

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. Examples of energy carriers include air in ducts or in a gravel bed or a fluid in pipes with high conductivity flanges.

4.5.2 Competitiveness

The cost of a 120 m borehole is in the order of magnitude of 10,000 Euro The cost for 200 m^2 of 400 mm EPS insulation is in the order of magnitude 4,000 Euro. Under a new building some insulation is needed in any case and this can 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 of introducing elements to enhance transversal heat flow from the pipes to the surrounding masses.

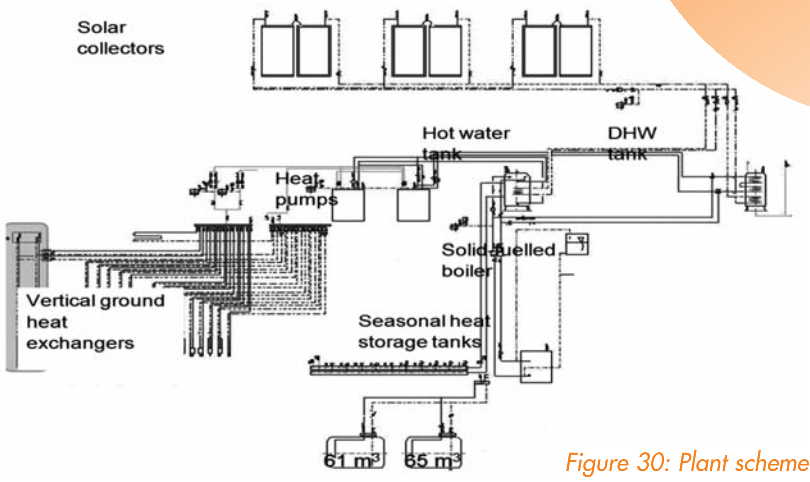


Figure 30: Plant scheme.

For a single borehole energy storage on an annual basis is not realistic. However, in cases were energy is extracted without any recharging, the borehole could be preferable.

4.5.3 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. On the other hand special attention needs to be paid to the diffusion of moisture from the ground. Still to be accurately evaluated are the environmental feasibility andthe effects of the changed conditions for vegetation on top of insulation. A particular concern are the global climate, local climate and health and comfort. Costs of the increased use of

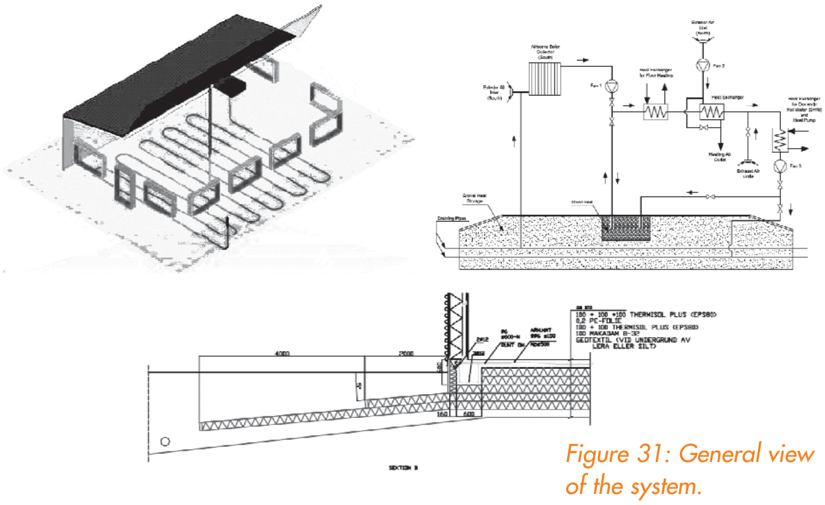


Figure 31: General view of the system.

insulating material compared to normal foundation and a drilled borehole are yet another concern.

Finally, an important issue for this solution is the auxiliary power for the energy carrier.

4.5.4 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.

4.5.5 Relevance as low-exergy technology

As pointed in the previous case study, the ability to store energy is a prerequisite for an effective exploitation of many renewable energy sources and their integration with non-renewables. Since this will also increase the overall exergy efficiency, once again, low-ex design turns out to be a holistic process, where different approaches have to be simultaneously used and adapted to the actual needs of a building.

4.5.6 Simulation studies

Studies have been carried out for a constant flow system and a system with variable flow of the energy carrier (Lazzarotto, 2008). The Figure 32 shows results from a simulation with air born 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 one 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.

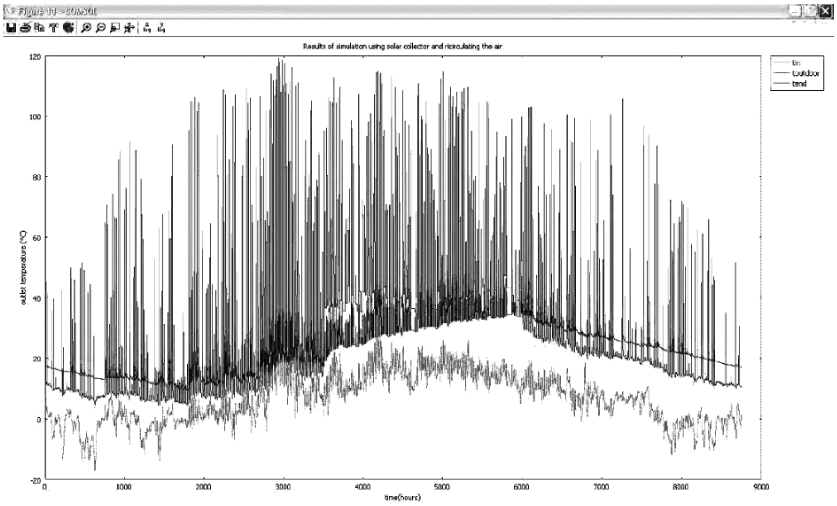


Figure 32: Temperatures in a yearly simulation.

4.5.7 Planned further activities

A two year project for field testing has been granted to KTH Building Technology 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.

4.5.8 Present evaluation statement (2008-09)

Simulations of 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 favorable conditions for supplying heating for the coldest month as well as the additional heat for the domestic hot water.

4.6 Exergy recovery from wastewater in small scale integrated systems[13]

4.6.1 Main features of the concept

In order to create a truly low-exergy building unnecessary exergy consumption must be eliminated. This includes the exergy lost by warm air as well as warm water released to the external environment. 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. Here, a recovery system is analysed to maximize the potential of warm wastewater to increase 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. In this system. a low lift compressor with a higher source temperature can then be used for the production of both low temperature (low-ex) space heating as well as hot water production, which requires a higher production temperature. The concept is illustrated in Figure 33 and the potential change in COP is presented in the T-S diagram (Figure 34).

4.6.2 Competitiveness

A public-private partnership is under development through the Swiss Office for Innovation between the ETH Zurich and Geberit AG. Geberit is the largest sanitary equipment manufacturer in Europe, and will be able to bring the concept to market as a pro-

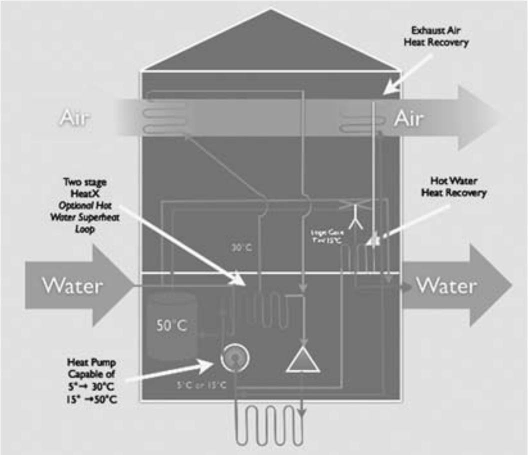


Figure 33: View of the system.

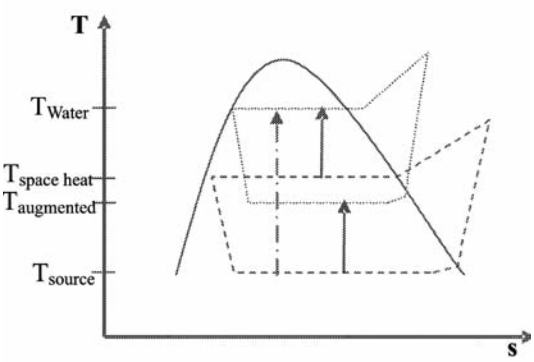


Figure 34: T-S diagram of the heat recovery process.

duct that will be widely available through Geberit's extensive distribution system. 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 offers an advantage as this provides a way to optimize the system such that the maximum quality energy is recovered, providing the most benefit to an integrated heat pump system.

4.6.3 Side effects

As a part of the system design, new technologies are also being implemented at Geberit. This includes new flushing mechanisms for rapid operation of the system. Very low-flow flushing systems are given proper drainage by a batch flushing process, along with ideal integration with new greywater separation and efficiency improvements.

This heat exchanger also allows Geberit to expand into simple systems for heat recovery, that simply preheat incoming water before it is heated in the hot water system, as opposed to a completly integrated low-exergy system. This makes simpler retrofits an option.

This research is carried out in collaboration with the Technical University of Lucerne in Horw (Switzerland). There, research focuses on new low temperature lift heat pumps with innovative compressor technologies.

Proper protection will have to be maintained to avoid any cross contamination in the system. Bacterial build-up and fowling of the system will be important to consider in the initial design as they could increase the need for maintenance.

4.6.4 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 is used in a Matlab model of a heat exchange tank. The tank is optimized for different heat exchanger fluid flow rates and tank size and shape in order to maximize the exergy captured.

4.6.5 Relevance as low-exergy technology

In this case study, the recovery of waste energy has a strong influence on the performance of the heat pump: by increasing the source temperature (see Figure 34) and consequently the COP, becase this decreases the demand for electricity.

4.6.6 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 35. This shows the annual exergy extraction as a solid line and the energy extraction as a dashed line as a function of the flow rate through the heat exchanger. When studying exergy, there is a 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, which indicated 400l as the optimal volume.

4.6.7 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 Buildings Systems group at the ETH Zurich. The project will contain other low exergy systems that are being evaluated and optimized in the group (Baldini, Meggers, Schlueter, 2007). The building, rendered in

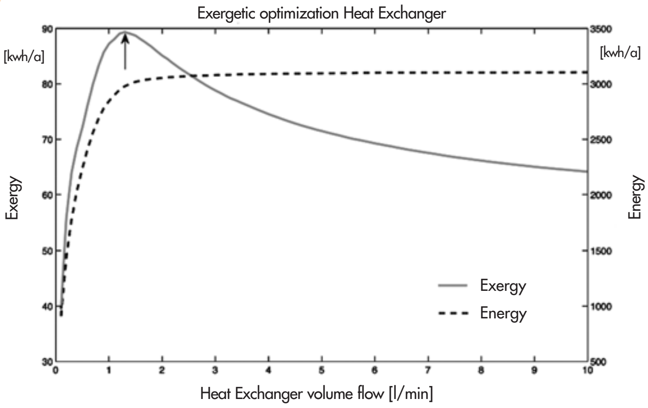


Figure 35: Exergy and energy flows.

Figure 36: Rendering of the monitoring building.

Figure 36, will be a four-apartment complex with an office on the first flow. It will be built over an existing old city water storage tank, providing an interesting 4m high space to do further experiments on building systems. The project will begin construction in 2010 and be finished in 2011.

4.6.8 Monitoring results

In the above pilot project performance of the system will be actively monitored, as it will be one of the first implementations. In addition to the wastewater heat recovery monitoring will include the borehole heat pump system, low exergy heating, the decentralized ventilation and centralized exhaust recovery. This data will also allow Geberit to finalize and upgrade their product specifications.

4.6.9 Planned further activities

The implementation and evaluation of the Bollystrasse 35 building in Zurich are described 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 will be 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.

4.6.10 Internet sites

www.gt.arch.ethz.ch
www.viagialla.ch
www.geberit.com

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[8] The authors of this case study are Xiaoyun Xie, Yi Jiang from Tsinghua University (China).

[9] The author of this case study is Xiaoyun Xie, from Tsinghua University (China).

[10] The author of this case study is Giacomo Villi from the University of Padova (Italy)

[11] The author of this case study is Tamás Simon from the University of Technology and Economics, Budapest (Hungary)

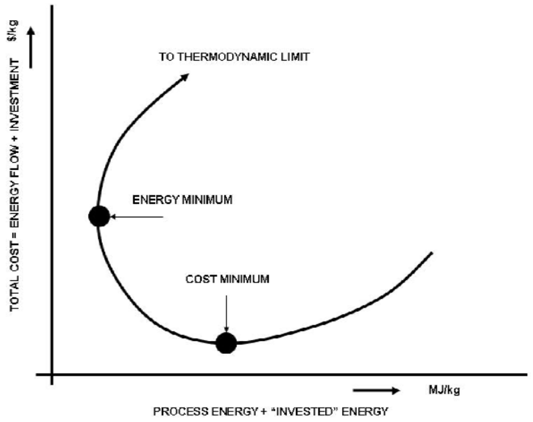
[12] The authors of this case study are Alberto Lazzaroto, Jorge Noguera and Gudni Jóhanneson from the KTH Royal University of Technology, Stockholm (Sweden)

[13] The author of this case study is Forrest Meggers from the ETH University, Zürich (Switzerland)

5 EXERGY APPROACH FOR NEIGHBOURHOOD AND COMMUNITY DESIGN[14]

To supply energy to communities around the world to date little attention was paid to the type and availability of the energy source used or whether it was the most appropriate source for a particular task. In North America, the need for easy access to fossil fuels (predominantly oil and natural gas) has overridden any concerns about resource management. Any issues of suitability have been dealt with by conversion technology. However, as the fuel market matured in North America and entered a period of uncertainty, utilities recognised a need to manage supplies to maximise the availability of what is, after all, a finite and increasingly valuable resource.

At the municipal or city scale an even greater diversity in energy supply is available to provide added security and economic stability for the citizenry. This diversity of supply and the possible use of local resources or renewable energy are balanced best at the neighbourhood level through legislative limitations, cost of installtion and the capacity of the developer to undertake the project. Conventional approaches to managing energy use at the neighbourhood level have resulted in the installation of solar, wind and earth energy. Yet, at the household level the decision to use such technologies is often based upon principle rather than on their economy. Often specific off-book financing, grants, debentures, etc are needed so renewables can compete with the established energy supply, be it natural gas, oil or electricity. Therefore it is generally felt that for renewable energy to become acceptable at larger scales without the use of unsustainable financial instruments a new business model needs to be developed that clearly articulates the difference in value rather than cost between fossil and non-fossil energy.



(From - Energy Policy: Fairy Tales and Factualities, Willem Van Gool)

Figure 37: Relation between thermodynamic optimization and cost of an energy system.

An approach to such a new business model that provides the degree of scientific rigour necessary would distinguish between energy forms using the thermodynamic property exergy. This science-based term describes the effectiveness of a system in transferring energy.

From an engineering perspective, a consequence of using a lower grade energy for heat transfer operations and thereby minimizing the overall exergy losses would be to increase the physical size of any heat transfer equipment. Improvements in exergy efficiency can be continued until the temperature difference between the two streams (warm water and room air) becomes negligible (Van Gool, 1997). However, this would require inordinately large heat transfer equipment. In reality, a compromise has to be found between thermodynamic excellence and engineering considerations.

The use of the exergy concept therefore provides an opportunity to link engineering and thermodynamic aspects (size, efficiency) with economic factors (opportunity cost). Creating a more consistent approach to energy selection in this way could offer the degree of rigour necessary to evaluate opportunities for managing their energy supply and demand.

5.1 Analytical approach

Based on the calculation method presented above (section 1.2) and on the MS Excel spreadsheet for analysis of energy systems on a building level, a spreadsheet analytical tool for analysis of community supply systems has been developped.

This tool represents the building as a simple thermal load and focuses on the energy supply and the distribution network. It represents the neighbourhood following the schema in Figure 38. The model neighbourhood consists of a centralised energy plant supplying a district heating piping network. The district energy concept is utilised to take advantage of a variety of energy supplies of differing supply conditions. Heated 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 although the three categories of buildings – high rise, residential and retail, are connected sequentially.

Keeping in mind the concerns relating to urban design and energy use and in particular the desire to reduce the need for fossil fuels as outlined earlier, 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 exergy 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?

The model includes an allowance for both space heating and internal electrical loads. Building details provided to the model describe 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 9 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 evaluation the district energy supply temperature is selected, based upon the capabilities of the supply technology. Five technologies have been 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

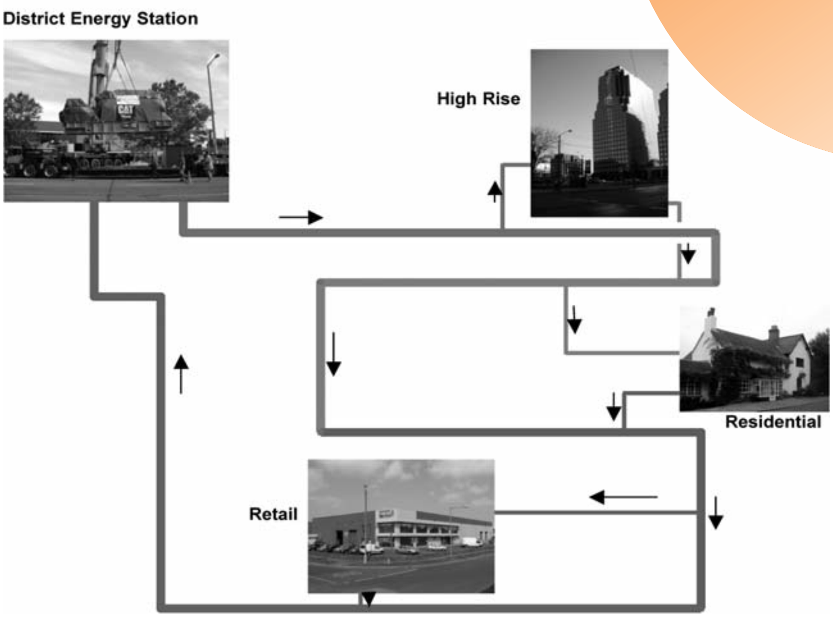
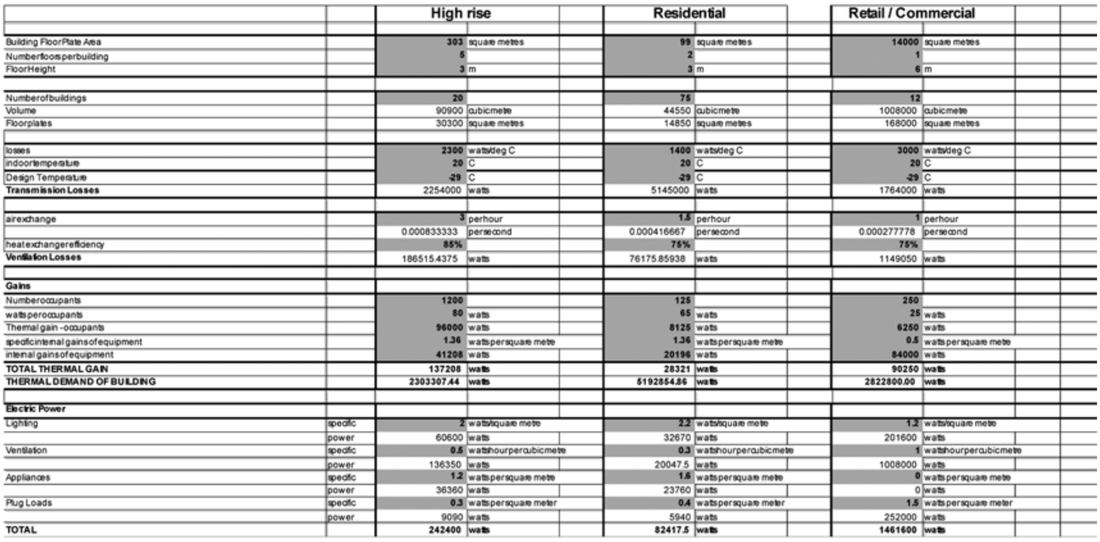


Figure 38: Neighbourhood model implemented in the community excel calculation tool.

For options 1 to 3, the initial exergy level is dependent on the combustion temperature of the fuel. Electrical power where not provided by the neighbourhood system (i.e. in options 1, 2, 4 and 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

Table 9: Building design data in the spreadsheet calculation model.



		High rise		Residential		Retail / Commercial	
Building FloorPlate Area		303	square metres	99	square metres	14000	square metres
Number floors per building		5		2		1	
FloorHeight		3	m	3	m	6	m
Number of buildings		20		75		12	
Volume		90900	cubic metre	44550	cubic metre	1008000	cubic metre
Floorplates		30300	square metres	14850	square metres	168000	square metres
losses		2300	watts/deg C	1400	watts/deg C	3000	watts/deg C
indoor temperature		20	C	20	C	20	C
Design Temperature		-29	C	-29	C	-29	C
Transmission Losses		2254000	watts	5145000	watts	1764000	watts
air exchange		3	per hour	1.5	per hour	1	per hour
		0.000833333	per second	0.000416667	per second	0.000277778	per second
heat exchanger efficiency		85%		75%		75%	
Ventilation Losses		186515.4375	watts	76175.85938	watts	1149050	watts
Gains							
Number occupants		1200		125		250	
watts per occupants		80	watts	65	watts	25	watts
Thermal gain - occupants		96000	watts	8125	watts	6250	watts
specific internal gains of equipment		1.36	watts per square metre	1.36	watts per square metre	0.5	watts per square metre
internal gains of equipment		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	watts hour per cubic metre	0.3	watts hour per cubic metre	1	watts hour per cubic metre
	power	136350	watts	20047.5	watts	1008000	watts
Appliances	specific	1.2	watts per square metre	1.6	watts per square metre	0	watts per square metre
	power	36360	watts	23760	watts	0	watts
Plug Loads	specific	0.3	watts per square meter	0.4	watts per square meter	1.5	watts per square meter
	power	9090	watts	5940	watts	252000	watts
TOTAL		**242400**	**watts**	**82417.5**	**watts**	**1461600**	**watts**

options. Heat distribution within the buildings can be either forced air or radiators where the radiator design is to DIN 255-3 (DIN EN 255-3:2008) standards for the supply temperature to maximise their efficiency of operation.

5.2 Case study – results from community analysis tool[15]

In order to demonstrate the application and show results of the exergy calculation proposal for communities, a simple case study was performed. For this purpose, a reference case was defined and compared to several energy supply systems on a community or district energy supply scale.

In the reference case a conventional district energy system is fed by a gas fired, standard efficiency boiler. All buildings in this case are connected in parallel and received water at 90°C. They returned it at 80°C with heat being distributed throughout the building using forced air circulation.

In the test cases the building types are connected in series so as to allow the district energy water to cascade thermally from the high rise to the residential and on to the retail buildings. To distribute the heat, the high rise and residential buildings utilise high efficiency radiators while the retail buildings are assumed to retain the forced air system.

The reference air temperature was -29°C, being representative for Canadian winter climatic conditions.

The results of the analysis are presented in terms of the primary energy requirements i.e. the fossil based energy required for the creation of all thermal and electrical needs of the system. Since the intent of the exercise is to demonstrate the impact of both technology and reduced demand for fossil fuel, information also provided on the following parameters:

- Energy efficiency of system – heating and electrical generation as a percentage of input primary energy – this illustrates the amount of energy usefully deployed as space heating or as available electricity. This would be a combination of the single energy efficiencies (see section 2.2) of the primary energy transformation and the generation subsystems as shown in Figure 5.
- Useful exergy efficiency of heating system – heating and electrical generation exergy as a percentage of available exergy – illustrates the exergy consumed in space heating and generation of available electricity. This represents the overall exergy efficiency for the electricity and heat production systems (see section 2.2 and Figure 5). It is defined as rational exergy efficiency (see section 2.1.2).
- 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. It is a sort of simple exergy efficiency (see section 2.1.1) for the overall heat and electricity supply systems, where the losses in the supply of electrical and thermal demand of the buildings are included as output, and the total exergy available in energy sources consumed is regarded as input.
- 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. This is similar to an energy efficiency for the heating and electricity generation systems, but only considers the fossil energy inputs.

5.2.1 Baseline case

This case assumes a district energy system that utilises a standard (medium efficiency) industrial boiler as the heating source. All buildings are connected in parallel and therefore receive the same hot water supply with a temperature of 90°C. After extracting their design heating load they return that water at 80°C. The buildings are heated with a fan driven forced-air distribution system. This approach is typical of Canadian district energy systems where the influence of alterations or commissioning within the customer building on the distribution network is minimal.

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 (Table 10).

Table 10: Main results for the baseline case.

	Primary Energy (MW)	Energy Efficiency (%)	Useful Exergy Efficiency (%)[16]	Total Exergy Efficiency (%)[17]	Fossil fuel [18] Efficiency (%)
Standard Boiler	20.4	57	3	3.8	57

5.2.2 Cascaded options

In this case the district energy 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, the return water is then fed into the residential buildings and finally their return is used by the retail sector. To maximise the distribution of heat within the various buildings, hydronic radiators are employed in the high rise and the residential buildings. As in Europe, the hydronic systems are designed according to DIN standards, appropriate for the temperature ranges associated with the building category. A forced air distribution system is 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 in overall system efficiency from the baseline value of 57% to 58.3% (Table 11) and this was largely due to the use of the hydronic system in the high rise and the residential buildings as the use of hydronic incurs a lower pumping cost. While not common in North America they are undoubtedly more efficient than forced-air systems, especially when the final elements, the radiators, are sized correctly.

Cascading of the energy loads within a district energy system does provide some improvement in exergy use, although not as large as sometimes believed.

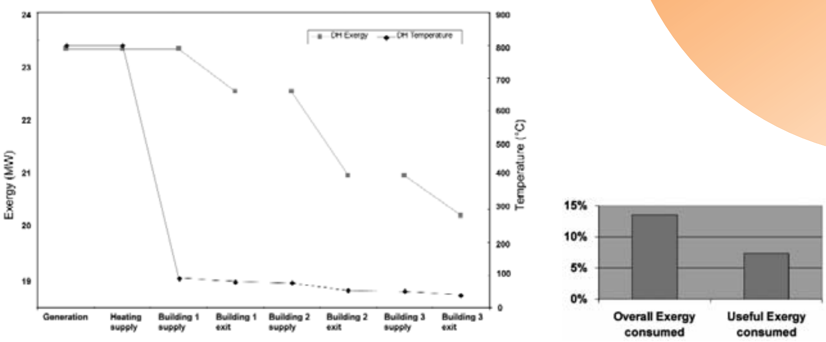


Figure 39: Cascaded option using standard boiler as energy generation system.

The exergy efficiency of the standard boiler (Figure 39) district energy system increases from 3% to 7.4%. For a high efficiency boiler system (Figure 40) it reached 9.5% implying greater use of the available resource but still leaving significant room for improvement. At this low level of exergy efficiency use 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.

The introduction of cogeneration (Figure 41) as both the thermal energy and electrical energy generator creates the most significant increase in the exergy efficiency. In the analysis, the cogeneration system is sized to supply the thermal load of the buildings. This is 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

Table 11: Main results for several options including cascading as energy supply strategy and renewable energy sources as energy generation systems.

	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	14.3	77	40	71	335	36

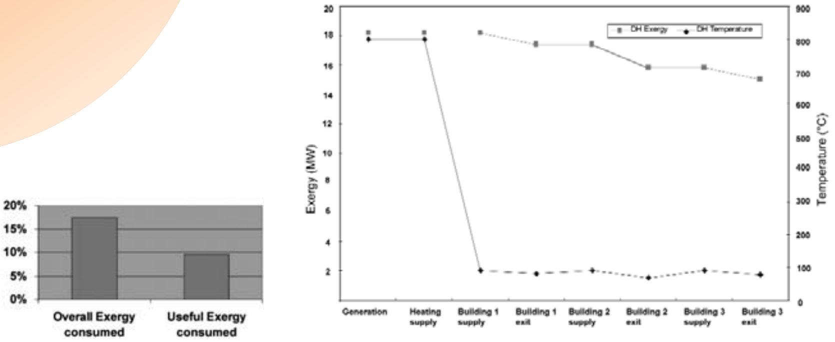


Figure 40: Cascaded option using condensing boiler as energy generation system.

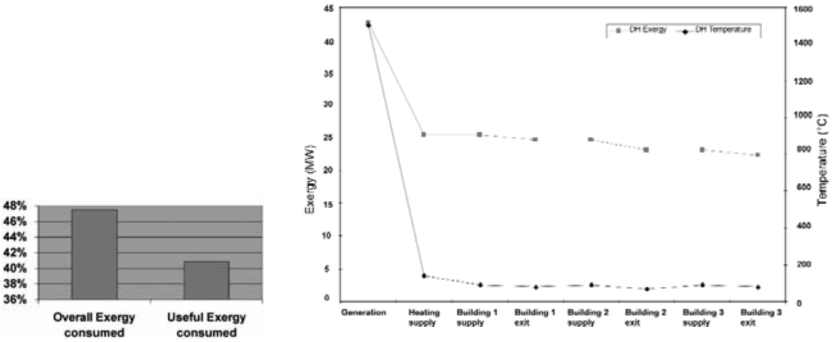


Figure 41: Cascaded option using a cogeneration unit as energy generation system.

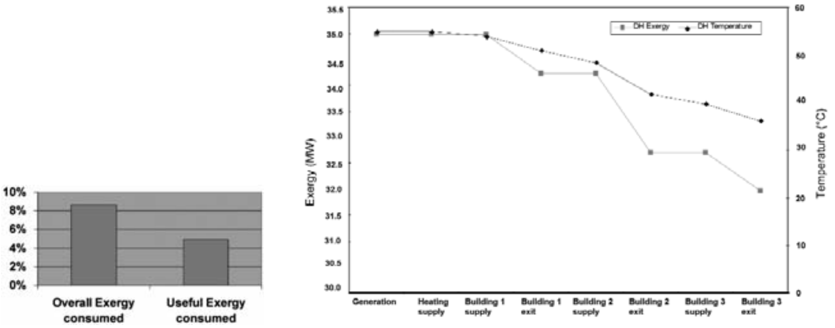


Figure 42: Cascaded option using a ground source heat pump as energy generation system.

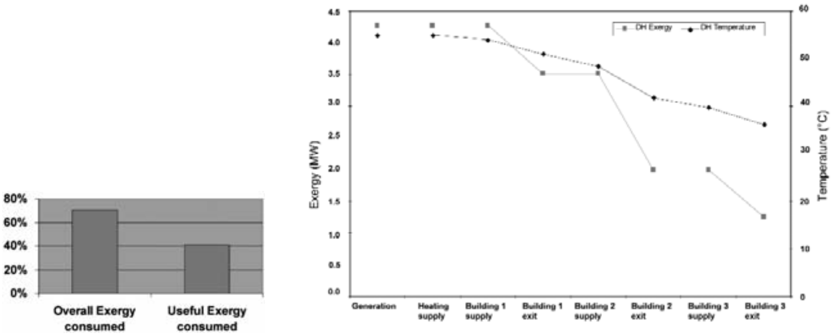


Figure 43: Cascaded option using flat plate solar collectors as energy generation system.

the excess generation. The approach would also consume additional gas to produce electricity, more than required for the building loads. Overall, from an energy perspective, the system is less efficient than a condensing boiler. However, from an exergy perspective there is a significant improvement over the boiler driven systems. This increase in exergy efficiency can be attributed to the generation of valuable electricity (exergy factor =1) from the unit.

The use of ground source heat pumps (Figure 42) as a heating technology is generally seen as a good use of renewable energy. However, while the need for fossil fuel heating is significantly reduced (from 20.4 MW to 11.5 MW) the efficiency of its use does not improve.

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 compressors, etc. This demand is, of course, dependent on the ground water temperature and the supply temperature to the buildings; the greater the temperature lift, the lower the pump's Coefficient of Performance 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, a preliminary version of a seasonal storage has been included in the calculations.

Figure 44 summarizes the results presented for the five cases. The "overall fraction of exergy consumed" is equivalent to the "total exergy efficiency", where exergy losses during the transmission process are included as output. In turn, in the useful exergy efficiency only the final useful exergy output is regarded (this is equivalent to the "desired" output in section 2.1.2).

5.2.3 Conclussions

From the basic evaluation presented here, several suggestions for changes to the design and operation of neighbourhoods are derived that will improve the use of energy and its exergy. These modifications range from the supply side through to the final end-user demand.

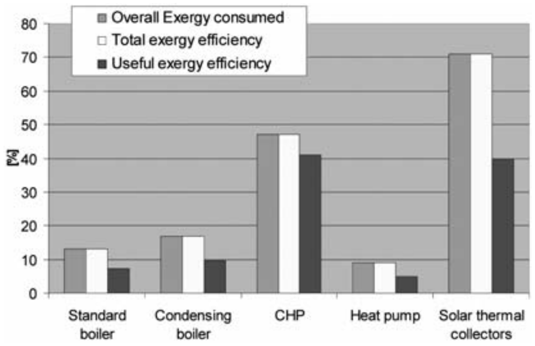


Figure 44: Overview of the overall and useful exergy efficiencies for the five cases studied here.

Within the buildings, a move away from forced air to hydronic distribution 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 or to a cogeneration system. This combination of changes will provide cost savings for the customer if not exergy improvements for the operator.

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

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

- 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.
- 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 would also enable the 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.

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[14] This section is based on an internal working report for Annex 49 by Ken Church from NRC Canada (Canada).

[15] Results presented in this section are from an internal working report for Annex 49, prepared by Ken Church from NRC Canada (Canada).

[16] Fraction of exergy used in producing useful work / heat.

[17] Fraction of exergy consumed (i.e including exergy losses)

[18] Pecentage thermal energy utiised per unit of fossil fuel consumed

6 INNOVATIVE 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.

The Community

Interestingly the term "community" is used by all 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.

The planning and decision making process

Figure 45 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 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.

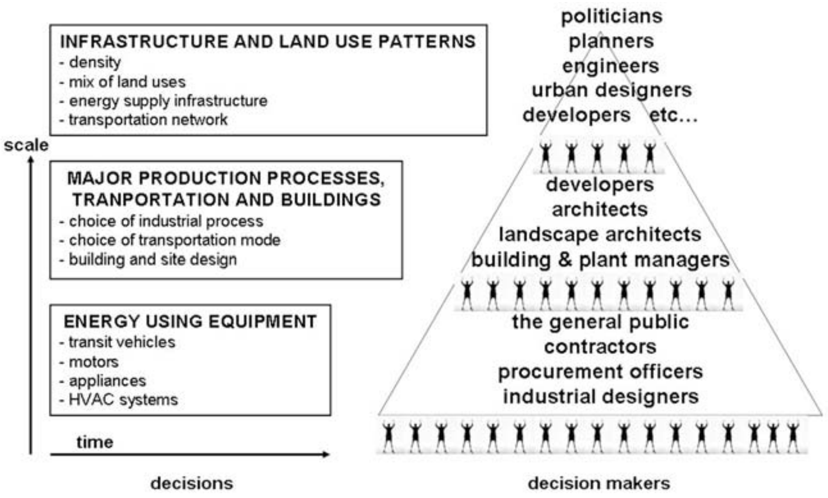


Figure 45: hierarchy of energy-related decisions

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 that a community planning tool is under development within IEA ECBCS Annex 49. This tool will provide a rigorous approach to the decision-making process.

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 availability 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.

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, 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.

In an arrow diagram (see Figure 65) the matching between the quality levels of the energy supplied and demanded is shown. The diagram, which was developed by Mia-Ala Juusela from VTT (Finland) is a qualitative representation of the quality and quantity of energy demands and supply in buildings. The height of the level at which the arrow is drawn indicates the quality (i.e. exergy) of the supplied or demanded energy flow. In a scale from zero to one, quality factors for different energy flows calculated according to equations in Table 1 are represented. The thickness of the arrows represents the amount of that energy demand or supply. By these means both the quality and quantity of the different regarded energy flows is shown.

The Primary Energy Ratio (PER)-Exergy efficiency diagram characterises the exergy performance and use of renewable energy in the supply of a community project. The diagram was developed by Erwin Roijen, from CHRI (the Netherlands).

The exergy performance of the community project is shown in terms of its exergy efficiency, calculated as a ratio between the exergy demanded and supplied. The PER is calculated as the ratio between the useful energy output supplied and the fossil energy flow in the supply. Higher PER values indicate a greater importance of renewable energy sources in the supply.

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. Examples of this situation are the community of Oberzwehren and Parma City.

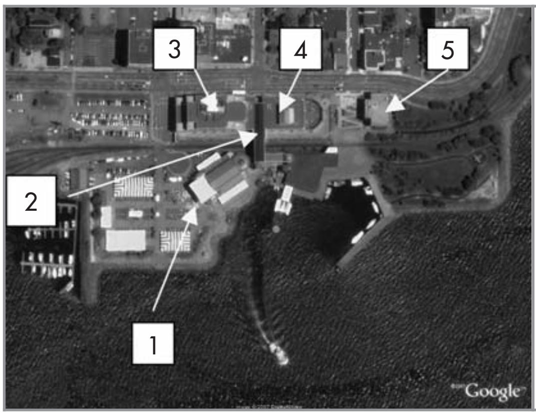
6.1 Alderney Gate (CA)[19]

6.1.1 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 46: Alderney gate complex (Canada)

Table 12: General project and system data for Alderney case study

GENERAL PROJECT DATA	GENERAL SYSTEM DATA
Municipality: Halifax Regional Municipality	Building Envelope Number: 5 Cooled Area: 30,741 m² (total) Cooling load: 500 tons
Constructor: High Performance Energy Systems	Maximum Seawater Supply Temperature: 8°C Maximum Seawater Return Temperature: 14°C
Installer: High Performance Energy Systems	
District Energy: High Performance Energy Systems	Annual cooling load: 2,500 MWh (thermal) Storage volume: 864,000 m^3 Borehole Storage Thermal capacity: 500 MWh (thermal)
Design Team: High Performance Energy Systems Environment Canada	
Hand-over: 2008	Borehole COP: 40:1

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.

6.1.2 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. 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. The technology will be installed in a car park site adjacent to the Alderney 5 Complex.

A peak seawater flow of 181m^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 located 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, 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.

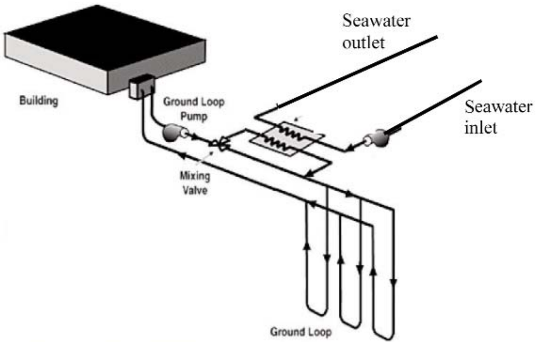


Figure 47: LowExergy cooling system

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.

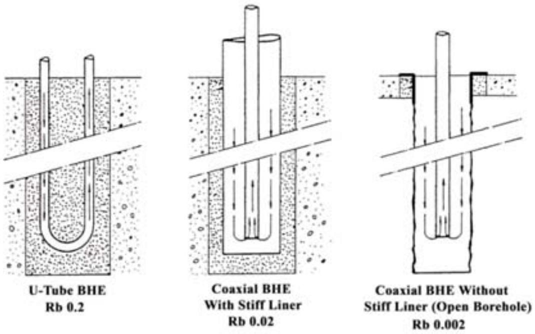


Figure 48: Advanced coaxial energy storage: heat exchanger design

6.1.3 LowEx Highlights and Diagrams

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.

LowEx Diagrams

Figure 49 shows the Primary Energy Ratio and Exergy efficiency for the energy mix regarded in the Alderney Gate complex.

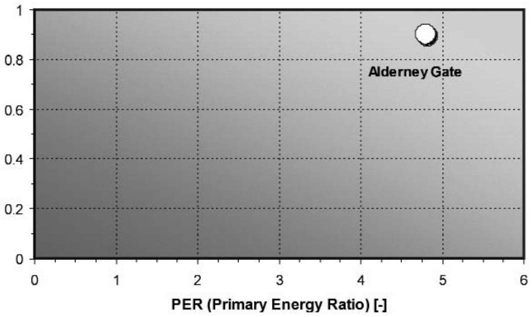


Figure 49: PER ratio vs Exergy efficiency diagram for the energy supply mix in the Alderney Gate complex

6.2 Okotoks (CA)[20]

6.2.1 General description

The community of Okotoks (Figure 50), 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 13.

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.

Figure 50: Okotoks complex (Canada)

6.2.2 Technical 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 51 a scheme of the solar thermal system, the borehole seasonal thermal storage and the district heating loop is shown.

The array is mounted on garages, at the rear of the houses and uses a propylene glycol/water solution, pumped through an underground pipe network to a heat exchanger and a high temperature, short-term thermal store (STTS) located within the 'Energy Centre'.

Two unpressurised epoxy-lined cylindrical steel water tanks form the STTS and internal baffles encourage thermal stratification. The Energy Centre also houses most of the pumps and controls.

In addition there is long-term Borehole Thermal Energy Storage (BTES) which contains 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.

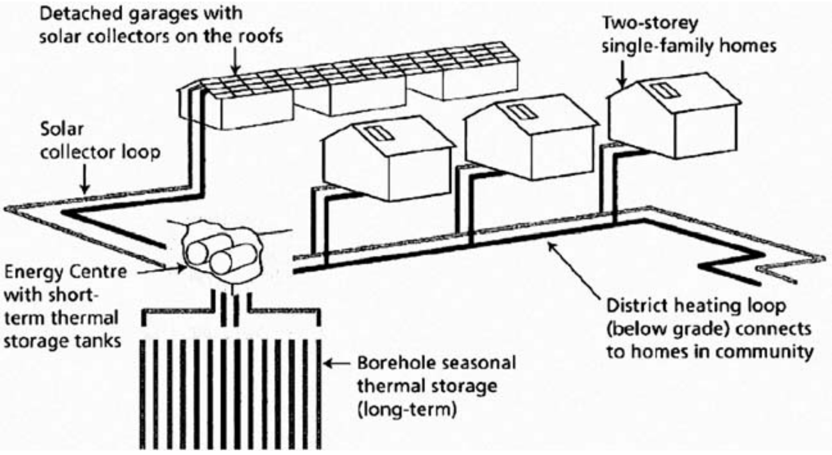


Figure 51: Solar seasonal storage and district heating loop

Table 13: General project and system data for Okotoks case study

GENERAL PROJECT DATA	GENERAL SYSTEM DATA
Municipality: Okotoks, Alberta Constructor: Sterling Homes Installer: Solar panels: Enerworks Fancoils: Nu-Air District Energy: FVB Engineering Thermal Storage: IFTech International Design Team: Natural Resources Canada, SAIC Canada, Enermodel Engineering Hand-over: 2007	Building Envelope: Number: 52 Heated Area: 240 m^2 (each) Specific heat load: 5.46 kWh/m^3 Supply Temperature: 55°C Return Temperature: 32°C Annual Solar Resource: 6.1 GJ/m^2 (1690 kWh/m2) Solar Collector Area: 2300 m^2 Solar Peak Output: 1.5 MW_{th} Annual Collector Efficiency: 29% (60-70% summer) Solar Delivered to Storage: 1.6 GJ/m^2 (455 kWh/m^2) Solar Delivered to Load: 1.0 GJ/m^2 (284 kWh/m^2)

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 52). Warmed air is distributed through the house via internal ductwork.

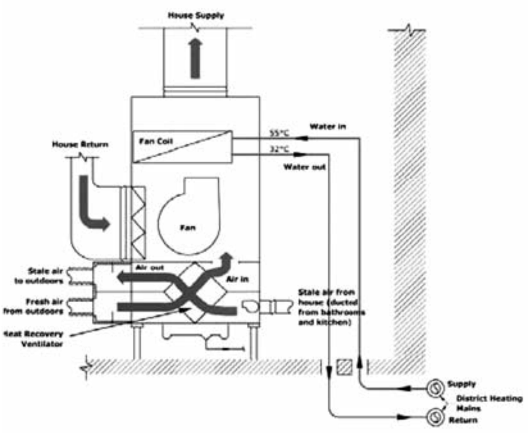


Figure 52: Heat emission: low temperature cooling air fan coils

6.2.3 LowEx Highlights and Diagrams

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.

LowEx Diagrams

Figure 53 shows the Primary Energy Ratio and Exergy efficiency for the energy mix used at the Okotoks Drake Landing Solar community.

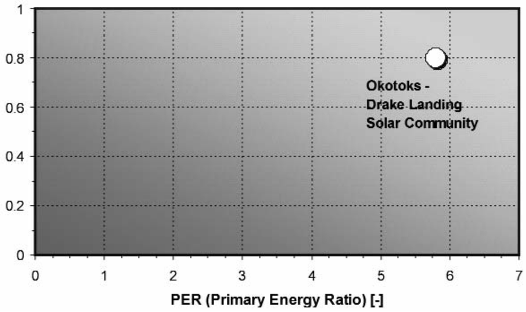


Figure 53: PER ratio vs Exergy efficiency diagram for the energy supply mix in the Okotoks Drake Landing Solar community.

6.3 Parma (IT)[21]

6.3.1 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.

During the last years Parma has undergone many initiatives related to energy efficiency measures for its community, with two energy plans (the last date back to 2006), local regulations for mobility, and the current project of a local mandatory buildings energy regulation with advanced quality certification tools and incentives for low energy and renewable energy technologies implementation.

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.

This work described here takes place in the framework of a research conducted by the unit Energy an Built Environment of the Building Environment Science and Technology Department of "Politecnico di Milano".

6.3.2 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.

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:

Figure 54: The city of Parma [source: Google Earth].

- 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 55.

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.

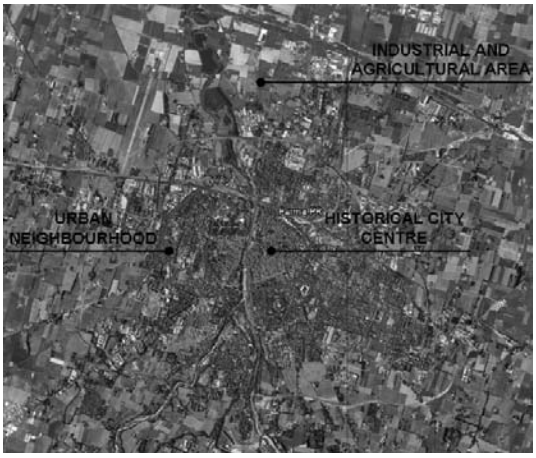


Figure 55: Districts that have been analyzed in the city of Parma [source: Google Earth].

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 56). Based on these real data and constraints we performed the energy and exergy analysis in order to define a realistic scenario.

Figure 56: GIS tool view.

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 and 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

Table 14: Energy characteristics of the three analyzed districts. Data from ENIA for year 2007.

	Natural gas [MWh]	Electricity gas [MWh]	Residential heated area [m²]	Residential units number	Total heated area [m²]
Historical centre	163531	59971	776780	8301	990975
Urban neighbourhood	156109	23470	545667	6511	736650
Industrial and agricultural area	61454	11164	165615	1956	190457

Table 15: Energy demand by end-use of the buildings in the three analyzed districts. Data processed from ENIA for year 2007.

	Heat demand				Electricity demand	
	Space heating [MWh]	Domestic hot water [MWh]	Process heat [MWh]	Other uses (cooking, etc.) [MWh]	Electric appliances, lighting [MWh]	Cooling [MWh]
Historical centre	88146	12271	-	15149	33984	25986
Urban neighbourhood	87762	9207	-	11882	16206	7263
Industrial and agricultural area	20627	2787	18690	3569	6094	5069

Table 16: 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%

Table 17: 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 (fossil fuelled)	67%
Renewable fraction of electricity from national grid	40%

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 14 and 15 present the energy characteristics of the three analyzed districts.

Scenario 1: Parma 2020.
Here, the objective is to find a realistic path to reach the 2020 European goals[22] by introducing mandatory regulation for local energy planning concerning urban planning and buildings refurbishment.

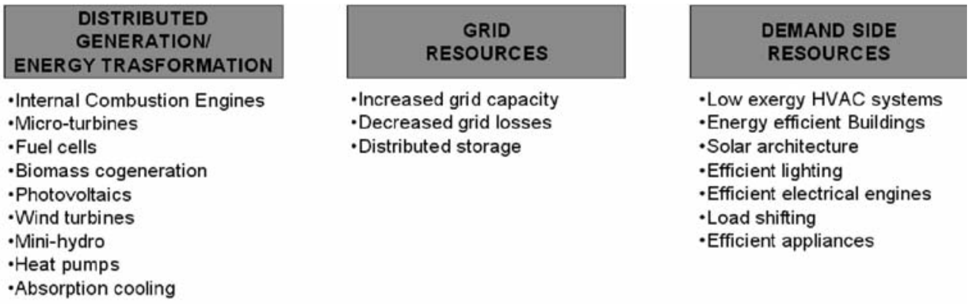
Scenario 2: Parma 2050.
The target is to transform Parma in a renewable city by the year 2050 adopting today best available technologies and practices as a benchmark. Here, the optimization of exergy fluxes will also be taken into account.

6.3.3. Technical description

6.3.3.1. Description of path towards new energy paradigma

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 Figure 57). 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 poly-generation 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.



DISTRIBUTED GENERATION/ ENERGY TRASFORMATION	GRID RESOURCES	DEMAND SIDE RESOURCES
•Internal Combustion Engines •Micro-turbines •Fuel cells •Biomass cogeneration •Photovoltaics •Wind turbines •Mini-hydro •Heat pumps •Absorption cooling	•Increased grid capacity •Decreased grid losses •Distributed storage	•Low exergy HVAC systems •Energy efficient Buildings •Solar architecture •Efficient lighting •Efficient electrical engines •Load shifting •Efficient appliances

Figure 57: Energy system organization.

6.3.4. LowEx Highlights and Diagrams

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 LowExergy 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.

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;
- Photovoltaic systems for electricity;

LowEx Diagrams

A graphical representation of the quality levels of the energy supply and end-use categories that will be considered in the optimization study is shown in Figure 58 andFigure 59. An indicative Carnot factor is reported for each category to allow a better comprehension of the quality of energy supply and demand. These assessments are preliminary and need to be refined further.

The scenarios Parma 2020 and Parma 2050 in which district heating and cooling were planned, refer to hypothetical energy plans that are currently being defined. The charts are for the winter condition in the two scenarios for the urban neighbourhood as already mentioned above.

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.

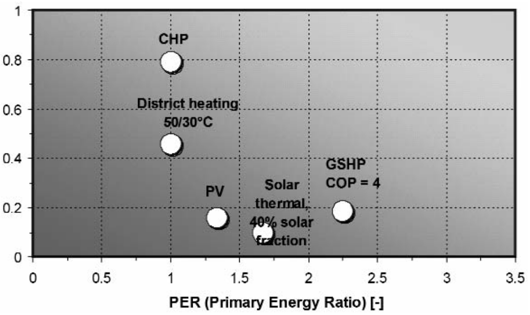


Figure 58: Diagram of exergy efficiency of the systems vs. primary energy ratio [Scenario 1 - Parma 2020].

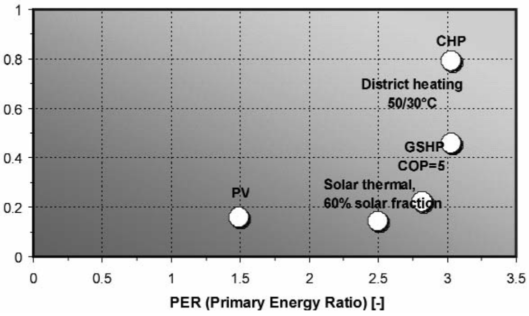


Figure 59: Diagram of exergy efficiency of the systems vs. primary energy ratio [Scenario 2 - Parma 2050].

6.4 Oberzwehren, Kassel (GER)[25]

6.4.1 General description

The city of Kassel, situated in the centre of Germany, is aiming at carrying out an environmentally ambitious housing project within the next couple of years. The building site is located on the estate of the former School for Horticulture of the University of Kassel in the city district of Oberzwehren (Figures 60 and 61). 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. The floodplain of a small river is located due 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 sensitise citizens to environmentally-friendly living in the city of Kassel.

Figure 60: Location of the building site [source: Google].

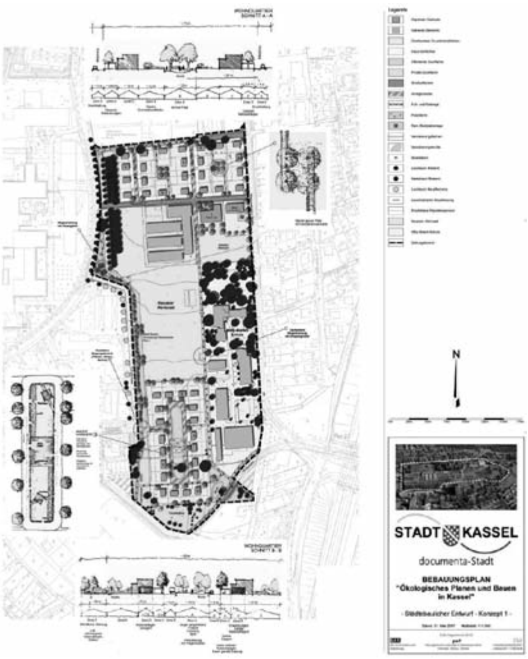


Figure 61: Basic concept for the estate development.

The goal is to develop an ecological building estate with high urban and architectural quality and to make an innovative energy supply system possible. In the year 2005, the planning office of the city council held a kick-off workshop with eight architectural and two landscaping offices from Kassel. The workshop resulted in four alternative distinguished urban concepts that formed the basis for a supply system concept.

The city of Kassel has set the ecological goal of a CO_2-neutral energy supply as the overall concept for the project. The concept aims at:

Minimizing the CO_2-emissions caused by the heating and DHW energy demand by high energy efficiencies and the use of renewable energy sources to achieve a neutral CO_2-balance.

Reducing the overall material and energy flows over the life-cycle.

Realising the goals in an economic way and with reliable and commercially available technology.

The project is meant to lead the way in adapting urban structures to changing climatic conditions. In the project, the heat supply for the new houses is based on the use and extension of the existing infrastructure. Since the targets were set at an early stage of the project, legal requirements in the development plan can be set for the buildings' side. The amendment of the German Building Code, BauGB (2004), has brought some new options for setting targets for CO_2-reduction at the community level. The question whether general climate protection can be addressed by the development plan has not yet been addressed by courts or legislators. The project Oberzwehren will provide representative experience with this issue. The limited size, the "downtown" location of the building site (recycling of urban building sites and redensification) and the general questions addressed, make the project a good example of an initial case study.

6.4.2 Technical description

Existing supply structure and energy concept

In the northern area of the building site, the local utilities operate a district heating line that supplies the buildings of the existing eco-nursery and the Professional School for Horticulture. The southern area is at present not connected to the district heating and because of the long distances and small loads to be expected, a connection is not an economic option. For this area, alternative energy supply concepts have to be developed.

The overall goal of the building development is to achieve a neutral balance in CO_2-emissions caused by heating and domestic hot water production (DHW). This is to be realised by renewable energy sources and efficient building design. The heating demand and the use of renewable energy sources must be adjusted and optimised.

An efficient use of energy is the necessary premise for low CO_2-emissions. To use renewable energy sources for heating purposes, radiant heating systems are suitable because they use low supply temperatures. To reduce the heating demand, the insulation level of the buildings will be set close to the passive house standard with a primary energy demand of about 40 kWh/(m²a).

Currently, there are two different building concepts under discussion for the project. The basic concept contains single-family buildings (Figure 62). The alternative is a more condensed structure with row-houses. Estimate of the average energy demand to be used in the planning process were based on standardised calculations in accordance with the German Energy standards for total heat demands and heat loads. With this data the local utility supplier was able to estimate the development costs for different energy supply structures.

The single-family buildings in the south have an energy demand for heating of about 78 MWh per year, with an additional 42 MWh per year for DHW. For the more condensed structure of row-houses in the north, the heating demand is about 87 MWh per year, while the demand for DHW rises to about 79 MWh per year because of the larger number of units. The total energy demand adds up to approximately 165 MWh per year for heating and about 121 MWh for DHW.

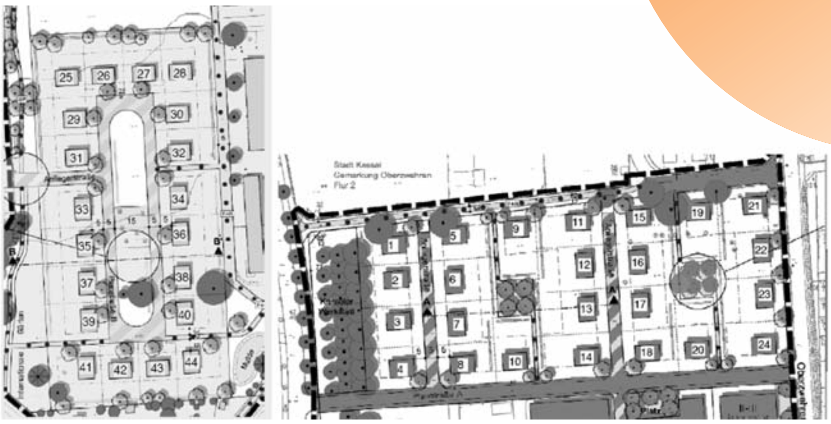


Figure 62: Building structure for the energy concept. In this case, both sites with single-family buildings.

The ideal orientation of buildings to minimize energy demand is always discussed during the first planning phases. Thermal simulations show that the building orientation is of minor significance for the heating demand because the solar contribution to heating decreases with better building insulation. On the other hand, for active solar energy use with photovoltaic and solar thermal collectors the building orientation and lack of shading by trees and neighbouring buildings is an important factor. Since the city has set a zero CO_2 target the substitution of the remaining fossil fuel demand by renewable electricity is an important issue. To achieve the goal the installation of PV will have to be a mandatory for the future building owners. Since the planners regard the east-west orientation of a large number of buildings in the southern building site essential for the appearance of the urban space, the issue of equal potential for use of solar radiation for all future building owners has to be solved.

Table 18: Energy demand of the buildings in the two building sites, Otto (2007).

	Total area [m²] / units	Heat Demand [kWh]	Heat Load [kW]	Domestic Hot Water [kWh]
Building site - north	13,430 m²			
Row houses	37	87,045.5	40,984.1	78,591.7
Building site - south	11,414 m²			
Single-family buildings	20	78,400.0	45,120.0	42,482.0
Total (including public green areas and roads)	85,612 m²	165,445.5	86,104.1	121,073.7

Heating systems will use temperatures close to room temperature, so that the supply will be very efficient, with minimal losses. Presently, high quality energy sources like oil and gas are used for the heating of buildings. Such sources produce high process temperatures and therefore contain a large exergy potential. This high potential is basically wasted by using these energy sources 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. These energy sources fit well to the demands of buildings and can be used cost-efficiently. To make use of these sources, the overall building system has to be adjusted to the low process temperatures. This leads to apply the LowExergy approach.

For the building site, an energy standard is to be achieved that is significantly lower than the current legal requirements set by the Energy Conservation Ordinance. The requirements 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

Innovative approaches for Legionella-prevention in DHW storages by alternative techniques.

In light of current climate change and the possibilities of rising temperatures and extraordinary hot summer spells, the cooling of residential buildings is becoming a significant issue. The cooling of residential buildings is not common in Germany today and according to recommendations in the Energy Conservation Ordinance the use of air-conditioning systems for cooling had to be avoided. In order to prevent over-heating in summer, the reduction of window areas and the use of shading devices are the only means architects have been able to use. The new Energy Conservation Ordinance, EnEV (2007) allows the use of technical cooling devices under the condition that the maximum primary energy demand for space heating cooling and DHW supply is not exceeded. In the course of the project, the exergeticly efficient cooling strategies will be tested to improve comfort for inhabitant of the new buildings. The use of underground heat exchangers in connection with the large area exchange systems is a promising approach.

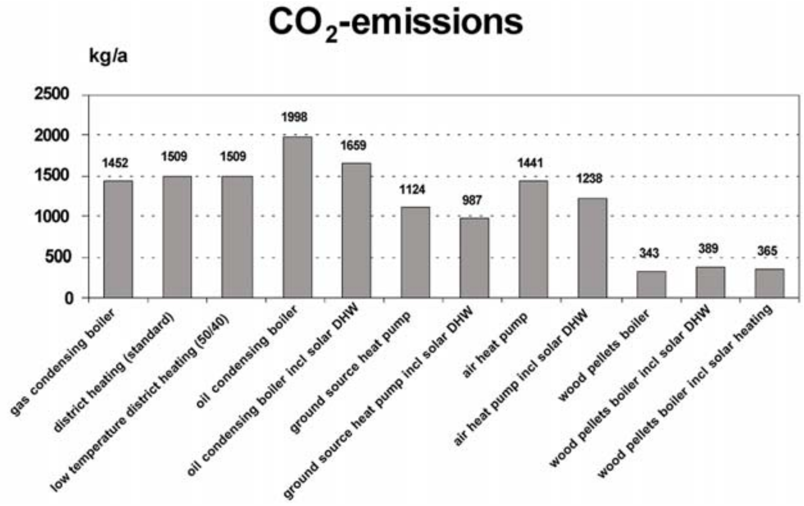


Figure 63: CO_2-emissions of system alternatives based on GEMIS 4.4 data, GEMIS (2007).

The northern part of the building site offers the possibility of having a district heating return line. This would allow to optimised exergy demand and avoide fossil fuel use. The existing district heating supplies several buildings with a large energy demand. The temperature level in the return line is high enough to supply heating energy for all the buildings planned in the northern area. The local utility providers have shown a great interest in the project, since the cooling of the overall return temperatures in the district heating grid would raise the efficiency of the heating plants. While the size of the building site in Oberzwehren is too small to significanltly increase the efficiency in the overall system, the utility suppliers expect important results for future developments from monitoring in this project. So while the extension of the district heating grid to the southern area can not be economically realised. the use of the return line in the north ought to be traced in greater detail.

The southern area will serve as a "renewable reference area". The area will be dedicated to single-family buildings with passive house standard and energy infrastructure may be limited to electricity only. Possible energy supply systems are heat pumps, thermal solar collectors and efficient ventilation systems with heat recovery. The different reference systems will be defined in the further course of the project. Because of the problems with respirable dust, the use of wood boilers will be avoided, even though the CO_2-emissions (Figure 63) would be very small using renewable fuels.

In order to be able to balance the necessary energy for heating and DHW, a certain roof area must be dedicated to the installation of photovoltaic. The electricity produced by the photovoltaic panels will be fed into the network and substitute electricity from conventional power plants. In this way, building owners will be able to balance the CO_2-emissions produced by their buildings. The calculations show that using the district heating concept the necessary PV-area can well be fitted on the available roof area (Figure 64).

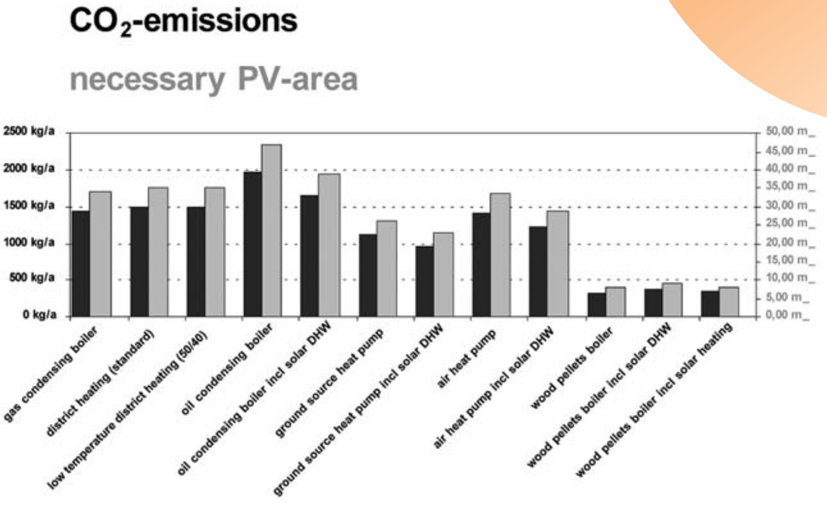


Figure 64: Necessary PV-area to balance the CO_2-emissions of the system alternatives.

6.4.3 LowEx Highlights and Diagrams

LowEx Highlights

In the project several "LowEx" technologies will be used: radiant heating systems, ground heating and cooling, solar thermal collectors and return water from a district heating pipe of an already existing district heating network. Furthermore, building shells will be optimised to maximise utility of the available low exergy sources and technologies. Therefore, the project is a great example of the practical application of design principles derived from the "LowEx" approach.

LowEx Diagrams

A graphical representation of the quality levels of the energy demand and supply is shown in Figure 65. The height-level of the arrows gives an idea on the degree of matching between energy supply and demand. In an ideal case supply and demand arrows would be equally thick (no energy losses) and at the same level(no exergy losses).

Quality levels of the energy supply and demand are calculated by using simplified steady state equations assuming a reference temperature of 0°C (typical winter space heating conditions in Germany), as well as typical supply temperatures for the technologies, sources and demands regarded. Supply and return temperatures assumed for the solar thermal collectors and district heating return pipe are assumed to be 70/50°C and 50/30°C, respectively. Approximate quality levels under these assumptions are displayed close to the corresponding arrows in the diagram.

Figure 66 shows the Primary Energy Ratio and Exergy Efficiency for the energy supply options evaluated for the community of Oberzwehren.

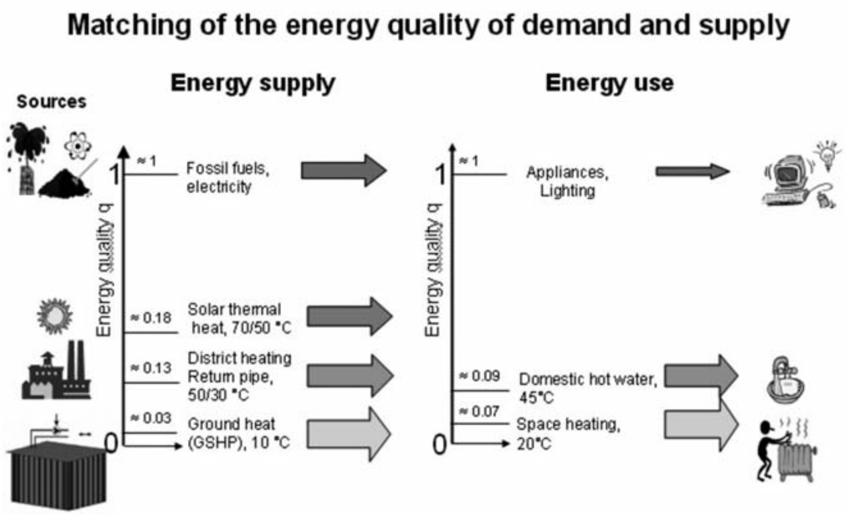


Figure 65: Matching of the quality levels of energy demand and supply for the community of Oberzwehren. The different energy supply options regarded as possible supplies are characterised separately

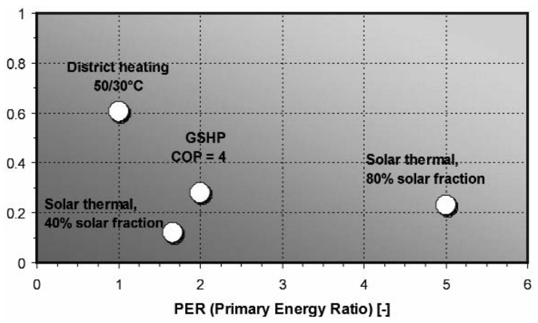


Figure 66: PER ratio vs Exergy efficiency diagram for the different energy supply options under consideration for the community of Oberzwehren.

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[19] The author of this case study is Ken Church from NRC Canada (Canada).

[20] The author of this case study is Ken Church from NRC Canada (Canada).

[21] The author of this case study is Paola Caputo, from the Politecnical University of Milan (Italy).

[22] 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.

[23] Not totally renewable but almost entirely fuelled by renewable energy.

[24] The scenario Parma 2007 isn't represented in the charts because the supply of the city is based only on fossil fuels used for electricity or for heating generation and all the systems are "high exergy".

[25] This case study is based on an part of a paper by Sager C. Concept for exergy balancing on community level for enhanced sustainable energy performance in a residential development in Kassel, Proceedings of the Nordic Symposium of Building Physics 2008, Copenhaguen (Denmark).

7 CONCLUSIONS

This midterm report gives insight in the conducted work during the course of the Annex 49 project and an overview over the findings of this team of international experts

Results from a literature review carried out as part of the research activities from Annex 49 highlighted the strong need for a common method of exergy analysis in buildings and building systems. Exergy analysis in buildings is very sensitive to the reference environment and analysis methodology chosen (e.g. dynamic or steady state; regarding humidity in indoor and outdoor air or disregarding it). Thus, the lack to date of such a common framework for exergy assessment in buildings makes the comparison of conclusions from previous exergy analyses very difficult. Therefore, one of the main focuses of Annex 49 is to develop and establish a common methodology for exergy analysis in the building sector. The present state of the art of this methodology, both for buildings and community supply structures has been presented. The analysis method follows a steady state approach, which can be implemented as is, or as a quasi-steady state assessment on top of dynamic energy simulations.

To establish exergy as a parameter for benchmarking and clustering the performance of building energy systems, the exergy expenditure figure has been proposed. It is a suitable indicator for characterising and comparing the performance of different energy systems that complements already established indicators such as the exergy efficiencies.

On a community level the suggested "Primary Energy Ratio – Exergy Efficiency diagrams" as well as the described "Arrow diagrams" enable decision makers to evaluate and compare a number of different system configurations against each other.

Insights into the method for exergy analysis have been complemented with the description of several case studies, both, on the community and building levels. Objects of these case studies are innovative building technologies or energy supply structures where the exergy principles play a key role and exergy analysis is being or will be applied.

The work of Annex 49 is going to be continued beyond the scope of this midterm report and will finally be described in a guidebook, the final Annex 49 report. This extended report which will also include an in depth explanation of the method of exergy analyses within the built environment will be available in summer 2010.

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ANNEX II: LIST OF PUBLICATIONS FROM ANNEX 49

2007

Angelotti A. and Caputo P. 2007. The exergy approach for the evaluation of heating and cooling technologies; first results comparing steady-state and dynamic simulations. Proceeding of the 2nd PALENC and 28th AIVC Conference, Crete Island, Greece, Vol. I, pp.59-64

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6th Annex 49 Newsletter. September 2009.
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ANNEX III: 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 19 shows an overview of the topics covered in each subtask and the countries and institutions leading them. In Figure 67 the four subtasks of Annex 49 and their interdependence is shown graphically.

Table 19: 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)
C	Exergy efficient building technology	Sweden (KTH)
D	Knowledge transfer and dissemination	Germany (Fraunhofer Institute for Building Physics)

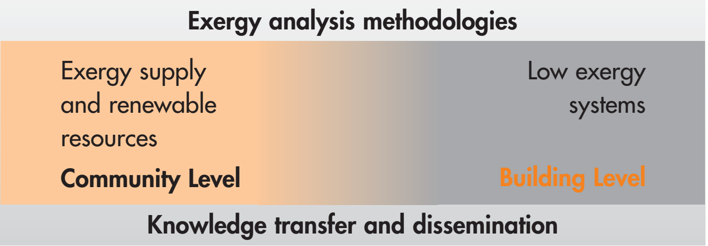

Figure 67: Graphical structure of the Annex 49.

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).

Annex 49 is a three year project. About 22 research institutes, universities and private companies from 12 countries are currently 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.

For the course of the project, the generation and supply is as interesting as the use of energy/exergy. As a result, the development of exergy efficient building technology depends on the reduction of exergy demand for the heating, cooling and ventilation of buildings. Finally, all results of Annex 49 are to be made public information. The knowledge transfer and dissemination activities concentrate on the collection and spreading of information on ongoing and finished work.

Annex 49
Low Exergy Systems for High-Performance
Buildings and Communities

International Energy Agency
Energy Conservation in
Buildings and Community
Systems Programme