IEA ECBCS ANNEX 49

Annex 49 is a task-shared international research project initiated within the framework of the International Energy Agency (IEA) programme on Energy Conservation in Buildings and Community Systems (ECBCS). ECBCS Annex 49 is a three year project. 22 research institutes, universities and private companies from 12 countries are involved.

The main objective of this project is to develop concepts for reducing the exergy demand in the built environment, thus reducing the CO₂-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.

www.annex49.com

COST ACTION C24: COSTexERGY

COST (European Co-operation in the field of Scientific and Technical Research) is one of the longest-running instruments supporting co-operation among scientists and researchers across Europe, allowing the coordination of nationally-funded research on a European level. COST enables scientists to collaborate in a wide spectrum of activities in research and technology. The COSTexergy project is one of the funded actions within this European programme.

The main objective of the COSTexergy project is to broadly disseminate new knowledge and practical design-support instruments that can facilitate practical application of the exergy concept to the built environment. In order to achieve this objective, the action relies on research activities carried out by its members, which focus on investigating and demonstrating how exergy analysis can be used in the development of innovative insights and concepts and support a wider deployment of low-valued heat and other renewable energy sources.

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The Future for Sustainable Built Environments with High Performance Energy Systems
Final event of the Annex 49 “Low Exergy Systems for High-Performance Building and Communities”

19th - 21st October 2010
Oskar von Miller Forum, Munich, Germany

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Welcome Note

Energy research policy positions Germany’s energy future. Technological progress is a basic component of future-oriented approaches in questions of energy and climate.

Focus concentrates both on energy efficiency and renewable energies. Successes in individual technologies are essential but a major breakthrough is only possible if intelligent system solutions are generated and implemented.

A good example for this are buildings and quarters: Only if building technology and systems engineering are planned with an integrated approach and harmonize with each other energetic optimum can be achieved. This integration includes both efficiency measures to reduce the total demand as well as the utilisation of renewable energy sources with innovative and highly efficient technology.

Low exergy systems promise further potential of improvement. Considering not only energy quantity but also its quality extends existing problem-solving measures.

The ECBCS Annex 49 is part of the German network “LowEx” addressing these subjects. This network, established as a thematic research platform in the framework of the research programme “EnOB: Research for energy-optimised building construction” of the German Federal Ministry of Economics and Technology, supports networking between different fields of activities and stakeholders and initiates cooperation between industry and research.

This conference brings together all interest groups and provides opportunities for lectures, project presentations, and discussion on possibilities and perspectives of low exergy systems. A main objective of this meeting is to give advice for future priorities in research activities. To achieve this your profound contributions are welcomed and you are invited to continue to take part in this ongoing process.

Dr. Hans-Christoph Wirth
Federal Ministry of Economics and Technology; Energy Research
What has been Achieved in Energy Efficiency?
– Implementation Strategies and Perspectives

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1. Become aware of energy efficiency

The terms ‘climate change’ and ‘energy’ are currently dominating TV news and light programs as well as magazines and daily newspapers. The urgency for taking measures to reduce greenhouse gas emissions as well as the adverse dependency on natural gas and oil suppliers is becoming a topic of top priority. Fortunately, the level of public awareness concerning this matter has improved due to the support of the media. A major contribution that started this re-thinking process was the so-called “Stern Review”\(^1\) [1].

The necessity to reduce the consumption of coal, oil, natural gas and uranium, which has been recognized in the meantime, can be achieved by the following three measures:

1. Reducing the energy demand
2. Enhancing the efficiency of provision and conversion
3. Increasing the use of renewable energy sources.

In recommendations for action concerning the future energy supply [2], these three sectors are also termed E\(^3\). However, the effects and the attractiveness of these measures are very different and will be discussed in the following.

2. Importance of the “Building(s)“ Sector

In Germany, almost 40 % of the total final energy consumption is used for the conditioning of buildings – for heating, cooling, domestic hot water production, artificial lighting, ventilation (see Fig. 1). More than one third of the final energy consumption is used for space and DHW heating, the greatest share being consumed by private households. This is a quarter of the total final energy used in Germany!

\(^{1}\) The **Stern Review** on the Economics of Climate Change was released for the British government on 30 October 2006. It was prepared by former World Bank Chief Economist Sir Nicholas Stern, now head of the British government’s economic service. The 650-page report discusses the effect of global warming on the world economy.
Conference “The Future for Sustainable Built Environments with High Performance Energy Systems”

Figure 1: Final energy consumption (delivered energy use) acc. to fields of application in Germany in 2005.

Analysing the final energy consumption in private households, two developments can be observed. On the one hand, the total final energy consumption for heating, lighting and electric appliances in private households has risen by 13% between 1990 and 2006. The final energy consumption for heat generation turns out to be different, though: between 1990 and 1996 there was a continuous increase in consumption, but since 1997 the energy consumption in residential buildings has been declining [3].

In contrast to other sectors of energy consumption, additional positive effects are achieved by taking structural measures to save energy costs for heating. The improvement of thermal comfort in buildings in winter as well as in summer is of special importance in this context. In many cases, modernization measures are required to preserve existing buildings and to conserve their value.

3. Defining 'improvement in energy efficiency'

Lately, the first two E³ measures, namely the reduction of demand and the enhancement of the efficiency of provision and conversion, have also been summarized by the term 'improvement in energy efficiency'. By introducing this term it was intended to eliminate the misleading expression of 'energy savings' (as from the physical point of view this is impossible) as well as to improve the image of this measure ('to save' evokes rather negative, 'to improve' rather positive associations). In many cases, a definite classification is actually not possible; so summarizing these concepts under the term 'improvement in energy efficiency' is reasonable and continuative, for instance this was done in the EU Green Book and in the EU Action Plan for Energy Efficiency [4, 5]. The word 'energy-efficient' thus implies low consumption and high efficiency concerning the meeting of demand. It is the amount of energy that is actually needed to secure the designated use.

4. Energy efficiency implies the largest potential

Special emphasis on the fact that the increased use of renewable energy sources should always be considered in connection with measures to improve energy efficiency can be found in the media and politics. First of all, measures to improve energy efficiency are of considerably higher practical importance than the increased use of renewable energy sources, which is also necessary. In 2005, for instance, renewable energy sources accounted for 62 TWh of the electricity production and for 81 TWh of the heat production (with a share of 69 TWh for wood) in the Federal Republic of Germany.
4.1 Passive use of solar energy

Figure 2 shows the shares of the amounts of energy produced by various renewable energy sources. If these amounts are compared to the amounts annually produced by the use of passive solar energy of residential buildings, the result is of the same order (an average amount of 83 TWh). In the process, only solar energy that is actually usable for heating is considered, the effects of overheating or unused solar energy (due to window ventilation or solar protection devices) have already been deducted. This passive use of renewable energy sources is however not addressed, it is simply taken for granted although it holds an enormous potential for improvement, for instance by making use of fenestration systems with good thermal insulation properties and the option of intensively absorbing solar energy.

![Graph showing the use of renewable energies in Germany in GWh](image)

**Use of Renewable Energies in Germany in GWh**

- **Electrical** \[\Sigma = 70433 \text{ GWh}\]
- **Thermal** \[\Sigma = 89543 \text{ GWh}\]

Figure 2: Use of renewable energy sources in Germany in 2006 for electricity production (yellow columns) and heat production (green columns) in comparison to the use of passive solar energy in residential buildings [6].

4.2 Efficiency potentials

As far as existing buildings in the Federal Republic of Germany are concerned, the potential to reduce energy consumption is still very large, since the energy performance of the building stock has not been optimized [6-9]. Due to the Thermal Insulation Regulations (and later the Energy Conservation Regulations) requirements for new buildings were enhanced, resulting in the reduction of energy consumption as specified in Fig. 3. Reasonable lower limit values for the energy demand were identified in demonstration projects (the grey area reflects the practical application to new buildings). Renovation measures performed in existing buildings in the last few years resulted in considerable reductions in consumption. Figure 4 represents the savings in heating energy that were achieved for residential buildings that were modernized in the scope of the BMWi (Federal Ministry of Economics)-funded project “Low-energy retrofitting of existing buildings (EnSan)”, the average of which is at 50 % [8].
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Figure 3: Development of energy-efficient construction in Germany.

Figure 4: Compilation of savings in heating energy that were achieved in the German EnSan-Project [10].
Even higher energy savings were achieved in other renovation projects, which is documented by the absolute values given in Figure 5. Here, savings could still be realised.

**Figure 5: Energy consumption of various residential buildings before and after retrofitting, depending on the building age category [11].**

Considering advanced renovation technologies and particularly aspects of rising energy costs, a reduction in consumption by about two thirds on average seems to be realistic. This means a savings potential of 640 TWh for the stock of residential buildings alone. Figure 6 illustrates this saving potential in comparison to the yields from renewable energy sources.

Thus measures to improve energy efficiency comprise a potential which is by an order of magnitude higher than the amount presently contributed by renewable energy sources. Improving energy efficiency in buildings is most important to solve energy problems. Regarding measures designed to improve energy efficiency, issues of acceptance are significantly less controversial compared with renewable energy sources such as hydropower, wind and geothermal energy. Furthermore, numerous measures to improve energy efficiency have positive additional effects, e.g. enhanced thermal comfort, increase in value as well as the conservation of existing buildings.
Figure 6: Use of renewable energy sources in comparison to the improvement in energy efficiency in residential buildings in Germany, based on a reduction in energy consumption by two thirds in the residential sector [6].

This should not be seen as a conflict here - it should rather be made quite clear that the improvement in energy efficiency is required as a solid basis for any reasonable measure to be taken, which could then be supplemented by renewable sources of energy. For instance, plus energy houses (which are expected to have become the standard by 2020) that work like “miniature power stations”, producing more energy than they actually consume, can only be realized by applying all of the available measures for improving energy efficiency and by making intensive use of renewable sources of energy, and by using solar energy in particular.

5. Political measures for raising energy efficiency

There are various measures available to increase the energy performance of buildings. The least expensive method, which (in theory) could also be realized most rapidly, is changing the users’ awareness. The so-called ‘cooling boxes’, which can be found at almost every window in many southern European countries, may work very efficiently - yet they would become unnecessary if solar protection devices were applied. In many cases, there is simply a lack of understanding for the underlying relations.

5.1 The new energy performance of buildings certificate

The energy performance of buildings certificate, which was first presented in 1989 [12], having been extended to large sections of the building stock since 2008 (according to the German Energy Conservation Regulations of 2007 [13]), will contribute to improve understanding and create more awareness.
What has been Achieved in Energy Efficiency?

5.2 A change of attitude – Making energy efficiency a top priority

Unfortunately, the energy performance of buildings certificate favoured by the German government gives reason to doubt whether it will have any impact at all, because the federal government conceded freedom of choice between demand-based and consumption-based certificates.

The essential purpose for introducing the energy certificate is giving information on the building energy performance and encouraging renovation measures to retrofit existing buildings.

On the basis of a demand-based energy certificate, qualified issuing bodies are able to identify the causes for high consumption values and to explain the effects of individual retrofitting measures. Considering additional aspects (like costs, preservation of the building substance, life cycle or protection against noise and moisture) an individual energy retrofitting concept can be developed in collaboration with the investor.

Although stating consumption data might be conducive for ranking one’s own consumption compared to average values, it is not suited to fulfil the function of energy labelling. Consumption values do not provide an objective set of criteria for potential buyers or tenants, because they are highly dependent on associated user patterns; deviations due to divergent usage are sometimes more than 100%. In addition changing meteorological boundary conditions are also possible causes of an erroneous
ranking - which cannot be rectified by simply correcting the heating degree days, because fluctuations of solar energy supplies during the heating season will remain unaccounted for. Additional sources of heat like tiled stoves or open fireplaces are not included in the heating bill, and relating solid or liquid fuels to the accounting period is quite problematic, leaving ample space for manipulation.

It is not possible to give building-specific recommendations for modernization based on consumption-oriented building energy labels, as only the current condition is regarded under undefined boundary conditions - and even this is the result of an unclear process: which share is due to which structural components or to which building systems? Either, remedial action cannot be taken at all or it lacks a reliable basis.

The comparatively moderate costs for issuing a demand-based energy performance certificate are justifiable with regard to the detailed building data providing comprehensive knowledge and with regard to the lack of an equivalent alternative. While energy consumption data provide useful building information, a consumption-based building energy label is of no value at all; actually, it frustrates the opportunities that energy retrofitting opens up for property owners, planners, craftsmen, industry, the economy and the environment.

Consequently, extensive marketing measures should be launched to support the demand-based energy certificate, with the aim of rapidly promoting the energy efficiency of buildings. Energy efficiency must have top priority.

6. Technical measures to increase the energy performance of buildings

To improve energy efficiency in the building sector, a great variety of technical measures are available:

- **Reduction of transmission heat losses**
  - additional thermal insulation
  - use of advanced energy efficiency windows
  - reduction of thermal bridges
  - coating of surfaces
  - reduction of the surface-to-floor area relation $A/A_n$

- **Reduction of ventilation losses**
  - sealing of air leakages
  - measures to obtain demand-controlled ventilation
  - use of mechanical ventilation systems
  - ventilated facades, earth ducts

- **Increase of solar gains**
  - glazing with high solar transmittance
  - glass annexes
  - transparent insulation, hybrid transparent insulation
  - solar collectors, photovoltaics

- **Increased efficiency of heat generation**
  - heating
  - domestic hot water
  - control systems
What has been Achieved in Energy Efficiency?

- **Increase of daylight availability and the efficiency of luminaires**
  - transparent or translucent building envelopes with high light transmission values
  - systems for daylight redirection
  - control systems

- **Measures to avoid cooling**
  - solar protection
  - night ventilation systems
  - thermally activated building components
  - heat storage capacity/ application of phase change materials

Most of these measures have already been widely realized and passed practical testing. Regarding both details and comprehensive new solutions, there is still a great amount of development and research work to be done to achieve systems with clearly higher efficiencies at lower costs. To prevent building damages and the deterioration of thermal and acoustic indoor comfort, an integral approach considering all processes related to building physics is required. Novel systems for managing renovation measures, designed to reduce the usual trouble between users and persons charged with executing these measures, are also part of these innovations. In this context, the so-called 'modernization holidays' may be mentioned as a vision, allowing to perform the trouble-free energy retrofitting of a complete building during the three-week vacation of the occupants.

7. **Buildings need to undergo “test runs”**

Besides the energy efficient design and construction of a building, the energy efficient operation of buildings is also required. Buildings featuring extensive building services engineering need to be given special attention, since their operation is often not energy efficient at all; rather, considerable reductions in consumption would be possible at relatively low cost.

Extensive monitoring to determine and analyse essential parameters will identify weaknesses in the operating procedure. Technologies such as Radio Frequency Identification (RFID), which are already available or are to be expected in the near future, allow wide-range applications.

8. **Demand for further Research and Development**

There is a considerable demand for research and development in order to achieve clearly more efficient systems that are less expensive, and this demand exists for both new details and for complete solutions. Good energy retrofitting measures always include improved thermal comfort, and energy-efficient buildings are the basis of a high real estate value.

9. **Certificate of Sustainability**

To be able to assess the sustainability of buildings, the Federal Ministry of Transport, Building and Urban Affairs (BMVBS) and the German Sustainable Building Council (Deutsche Gesellschaft für nachhaltiges Bauen, DGNB) jointly developed a quality label, which was to be introduced in Germany early in 2009. The Fraunhofer Institute for Building Physics (IBP) played a major role in the developing process: mainly the catalogue of criteria and the categories of the assessment system were compiled by expert scientists.
The German quality label “Sustainable Building” includes and documents the following aspects:

- Protection of resources
- Protection of the natural environment
- Securing and maintaining values
- Improvement of the surroundings and protection of public goods
- Assurance of health and thermal comfort of occupants

Main criteria of sustainability include:

- Ecological quality
- Economic quality
- Socio-cultural and functional quality

Also the following criteria are considered in the certificate:

- Quality of the technical execution
- Process quality
- Site quality

Figure 8 visualises the relations:

**DGNB German Certificate for Sustainable Building**

<table>
<thead>
<tr>
<th>Protection subject</th>
<th>Natural environment</th>
<th>Natural resources</th>
<th>Health</th>
<th>Economic values</th>
<th>Social a. cultural values</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Protection goal</th>
<th>Protection of the environment</th>
<th>Decrease of the life-cycle costs</th>
<th>Assurance of health/Thermal comfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protection of the natural resources</td>
<td>Receipt of ecological values</td>
<td>People-friendly surrounding area/Receipt of social and cultural values</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Assessment</th>
<th>Ecological Quality</th>
<th>Economical Quality</th>
<th>Socio-cultural and Functional Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical Quality</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process Quality</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site Quality</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 8: Structure of the German system for labelling sustainability.**

This structure allows the system to be adapted to different climatic or cultural boundary conditions whenever required, so as to be able to represent the advantages of German products in other countries. The German Sustainable Building Certification covers all relevant topics of sustainable construction. Six subjects affect the evaluation process: ecology, economy, social-cultural and functional topics, technology, processes, and location. The assessment is expressed in an overall rating, and the buildings are awarded labels in the categories bronze, silver, and gold.
10. References

[1] Nicholas Stern: Review on the Economics of Climate Change. www.hm_treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_index.cfm


Towards Energy Efficient Buildings and Communities

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The International Energy Agency’s Implementing Agreement on Energy Conservation in Buildings and Communities systems (ECBCS) is one the largest international collaborative agreement on energy efficiency for both buildings and communities. For more than 33 years, it has directed its research and technology development toward reducing energy consumption in buildings and communities, while minimizing environmental impacts. Today’s, it aligning itself toward the innovative challenges of the construction sector – buildings and communities- in terms of energy use and climate change, without affecting inherent clients needs such as health, and occupant’s satisfaction. The ECBCS website today has an activity of 2.5 M visitors/year, and reports have been downloaded more than 2 Million times. The primary receptors of these technologies and deliverables are primarily the various players in the business of the built environment such as those acting for design, operation and management, commissioning, and local energy planning.

The ECBCS has now completed 44Annexes – i.e. four-year research projects-, with major impact on energy efficiency and effective integration of new energy sources in buildings and communities. The ECBCS has recently completed its 2008-13 strategic plan. This process included, among other things, an environment scan and review of existing and emerging technologies, R&D and application in the built environment, with a special focus on energy and environmental impacts.

Today, the literature and current trends on energy use and environmental impacts demand immediate measures and strategies to reduce drastically energy consumption and environmental impacts from the built environment. The built environment - i.e., construction sector - represents more than 10% of GDP, but also consumes between 30-40% of total energy consumption and 50% of total primary resources. It is also responsible for 25-40% of the total solid waste. The sector is also recognized as uniquely fragmented especially in the decision-making process. It is critical to economy and people’s lives in all the world-, but widely recognized as slow in adopting innovative technologies. More than ever, the sector is facing challenging societal and regulatory demands, in aspects related to energy, ventilation, safety, etc. This coincides with the shrinking of R&D resources and investments, especially in the area of the built environment, and more demands from people for leadership and effective actions to tackle depletion of natural resources, mitigation of climate change, and increasing construction and occupancy costs.

As a result of the recent strategic plan exercise. The ECBCS is aligning its R&D activities towards the goal of near-zero energy and carbon emissions in the built environment by 2030. The ECBCS will build on its mission of R&D and innovation to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities. These technologies and processes will target a much radical decrease of energy

* On behalf of Executive Committee and Operating Agents
consumption and carbon emissions from buildings and communities. The aim is to impact three aspects of the industry’s business environment: decision-making; building products and systems; and dissemination. The basic strategies are focused on the keyword “integration” on three levels: integration of emerging sciences such as materials and ICT; integration of energy sources such as hydrogen, and integration of R&D and industry players for high impact projects and technology adoption.

During this 2002-07 cycle, the ECBCS completed 10 Annexes resulting in deliverables on improving energy efficiency and environmental impacts of buildings and communities. These are widely adopted by industry as standards, applied tools, and/or benchmarking. During this period, there were also 10 new Annexes, and related technology transfer activities. Examples include:

1. New Annexes on integration of leading edge technologies such as fuel cell, vacuum insulation, low exergy, LED lighting, etc.

2. New Annexes on integration of renewables and exergy.

3. New Annexes on key priorities: energy retrofit, energy efficiency for building services and envelopes, integrated life-cycle decision making; and energy efficient and sustainable communities.

4. More than 30 international conferences and seminars.

5. Future Building Forum workshops for forward outlooks on energy in built environment.

The ECBCS has now 13 large projects toward aggressive reduction of energy reduction in the built environment, and quantifying carbon emissions in new and existing buildings. Example of these projects include technologies and prototypes for net-zero buildings; energy retrofit in low-rise housing using prefabrication, energy guidelines and best practices for municipalities, low exergy application for buildings and communities, and method for total energy consumption for existing buildings. The ECBCS collaborates with other IEA building-related Implementing Agreements, national energy and building programs, as well as associations related to buildings, communities, and energy. For more information, please refer to:

www.ecbcs.org

Today’s member ECBCS countries include: Australia, Austria, Belgium, Canada, China, Czech Republic, Denmark, Finland, France, Germany, Greece, Italy, Japan, Republic of Korea, New Zealand, Netherlands, Norway, Poland, Portugal, Spain, Sweden, Switzerland, United Kingdom, United States.
The Role of Innovation for Energy Transition

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1 Introduction

To continue to enjoy prosperity while not exceeding environmental, social and economic limits, it is becoming necessary to pursue simultaneously business growth and reduced environmental degradation by substantially increasing the efficiency of natural resource usage.

Many incremental approaches to optimising resource efficiency are available. Businesses also need to consider potentially disruptive major ‘step’ changes offered by emerging technologies that create new options for resource efficient solutions.

Technology Management addresses the need to analyse the specific resource efficiency potential of a technology, relevant technological trends and opportunities for creativity when searching for new product ideas. It can help design resource efficient industry that have lower costs, increased security of raw material supply and reduced environmental impact. Hence Technology Management can be the basis for resource efficient innovations that improve productivity and open up new markets.

2 New technologies as a basis for resource efficient innovations

Technologies offer various solutions for resource efficient innovations. As well as supporting incremental approaches to resource optimisation e.g. ancillary units in production, businesses need to consider potentially disruptive major ‘step’ changes offered by emerging technologies that create new options for resource efficient solutions.

To secure a valuable eco-innovation, businesses need to take into account the availability of required materials (raw materials and components), the functionality underlying technology, the utility of the future product and its end-of-life impacts.

New technologies and their applications can play an important role in this context [9, 10]. They have the potential to increase resource efficiency in the following ways [11, 12]:

- new technologies can create new functionalities in existing or new application fields,
- new technologies can substitute existing technologies in existing or new application fields.

Such innovations can be triggered by different actors such as manufacturers, suppliers or customers and can drive cost savings - up to double-digit percentages [7]. Small-medium sized businesses have the potential for the biggest savings [8].

It is argued by many researchers that resource efficient innovations has substantial potential for opening up new markets (see [14]). Technologies and Products with high resource efficiency potential:
results from a cooperative identification- and selection-process. In this context, a cooperative identification- and selection-process was developed in order to identify such products and technologies (see Rohn et al. [10]). The procedure for selecting such technologies and products consisted of four steps (see fig. 1).

Developing resource efficient innovations – the Resource Efficiency TechnologyRadar

Developing resource efficient innovations through the adoption of new technologies is of increasing strategic importance for many companies. The use of new technological trends as an enabler for resource efficiency is able to complement existing resource efficient technology and product development methods such as environmental management systems, eco-design, environmental performance indicators or life-cycle assessment [25]. Technology management can be a powerful way to address this. An objective of technology management is to reveal opportunities and risks offered through the assessment of technological trends [26, 27].

In practice, the companies need to be clear about the relevance of technological options, many of which are still in a research phase. These can be identified and evaluated with respect to their potential for resource efficiency in future products and services. For leading-edge businesses it is important to be able to implement resource efficiency opportunities in the early phases of the technology development process.

The Resource Efficiency TechnologyRadar provides tools to methodically, organisationally and conceptually identify and assess technology trends to generate product ideas and business opportunities based on a business’s specific technology requirement profile (see [29]). The Resource Efficiency TechnologyRadar has been applied with and validated in several industry consulting projects. Based on typical technology intelligences, the “Resource Efficiency Technology Radar” is structured into the following four phases:
1. Identification of resource efficiency potential and resulting technology requirements,
2. Technology trend research and expert identification,
3. Expert interviews and trend assessment,

In the following, the four phases for developing resource efficient innovations were described and discussed.

3.1.1 Phase 1: Identification of resource efficiency potential and resulting technology requirements.

Based on one or several typical applications in the company, the resource efficiency potential is identified and evaluated. This is based on the following steps:

1. Definition of the assessment context:
   The assessment context includes the definition of relevant resources (material, substances, energy, etc.), approaches to increase resource efficiency (e.g. reduction of material consumption, substitution of material, increase of production efficiency), life cycle phases, system boundaries and components.

2. Estimation of product related information and material or energy flows:
   Analysis of major components and functions, based on available data from Life Cycle Assessments (LCA) and other sources. Description of input-output flows and processes, analysis of major processes, based on available data from e.g. material and energy flow balances.

3. Evaluation and classification of component functions and processes:
   With respect to step 1, components functions and processes are evaluated and classified according to their potential to increase resource efficiency.

4. Assessment, prioritisation, selection and clustering of identified topics:
   Based on the evaluation and classification in step 3, components and technologies are prioritised to cluster those with the highest potential to increase resource efficiency with the highest estimated cost-benefit ratio.

Under consideration of the resource efficiency potential, existing knowledge on technologies and their application as well as trend studies, future projections and expert knowledge are investigated in more detail. The results of phase 1 are formulated as a so-called “technology requirement profile” to guide all following phases of the methodology.

3.1.2 Phase 2: Technology trend research and expert identification

Based on the technology requirement profile, a trend research is performed consisting of the following steps:

1. Scanning the technology landscape within the Fraunhofer-Gesellschaft and in the research community (universities, industrial R&D, research organisations, etc) and assessment of future trends by evaluating future studies and future scenarios,

2. Identification of potentially valuable technologies and solution approaches (e.g. business models, service combinations, boundary technologies, etc.),
3. Identification of leading experts and lead projects in applied research to target interviews. "white spots" are identified in this step to detect additional topics and experts with potential relevance.

The results of the technology trend research and the identified experts are evaluated and prioritised with the company according to their relevance to the resource efficiency of products, services or processes.

3.1.3 Phase 3: Expert interviews and trend assessment

The goal of this phase is to evaluate the identified topics within the context of the company which acts in a certain market environment. Therefore, experts are interviewed to evaluate business opportunities, specific aspects of technology development or applications.

The potential of specific technologies for the company is thereby evaluated while taking environmental and market trends into account. Taking environmental aspects into account at an early stage in the technology development process is not an easy task (see [30]).

Environmental impacts can be caused by the selection of material and energy flows, the design, production and distribution, the use and the end-of-life-phase of products. The lifecycle of products has to be analysed in a holistic approach. This often requires a change of perspective from the conventional approach of merely looking at in-house product development, production and distribution of the product. This change of perspective is described by the term “lifecycle thinking” [30] and becoming more and more important in the context of combined product-service developments.

The assessment of the environmental impact of a product can be conducted by complex systemic life cycle assessment methods. They analyse and evaluate the whole-of-life impacts of raw materials and components, underlying technologies, functions and the use of the product. Examples for existing methods are LCA (ISO 14040), Simplified LCA [31] and Matrix Approach [32].

Generally, methods can be differentiated into Eco-Design and Eco-Indicator approaches. Eco-Design focuses specifically on the technical and creative development of the product itself [33, 34], while methods such as Eco-Effectiveness [35] and Material Intensity per Service Unit (MIPS) [36, 2] concentrate on specific indicators like the amount of toxic substances or resource productivity.

Most methods require specific information and data on the inputs to the product resulting from the application of the various technologies as well as the estimated use and lifecycle of the product. Hence, the methodologies are difficult to apply because they need a relatively detailed specification of the future product. The complexity of the methods and their requirements for information and data make a complete evaluation of technological trends and their contribution to resource efficiency of future products very difficult and costly.

However, sketching the expected lifecycle of future products can lead to consideration of possible environmental impacts and sensitivities so that, the most important environmental impacts can be identified. An example that enables the estimation of the resource efficiency of products based on the estimation of resource consumption throughout the product lifecycle is MIPS.

The MIPS methodology quantifies the material intensity of a product or service by adding up the overall material input which humans move or extract to make a product or provide a service [2]. It is measured in kilogram per unit of service. The material input is calculated in five categories: abiotic raw materials, biotic raw materials, water, erosion, and air. MIPS can be used to quantify consumption of resources and thus can serve as a good indicator for the evaluation of the resource efficiency of a certain application.
Within the context of the Resource Efficiency Technology Radar, the application of more detailed methods for the evaluation of the resource efficiency of technologies depends on the specific products, the context of the investigation and the level of information and data that are available.

The MIPS methodology represents in this context one of the most common methods as it provides a good balance between the ‘data intensity’ for its application and the quality of the results that can be achieved. Moreover, its applicability in an industrial context has been shown [12].

The results from the resource efficiency assessment allow companies to prioritise technologies according to their environmental impact and cost throughout the product lifecycle. This enables improved technology planning in a sustainable way within a long-term planning horizon in line with current market requirements. Technological trends and technology options are assessed with practical assessment criteria, including resource efficiency potential, market size and market growth, cost reduction potential, implementation risk, customer benefit, information requirement, accomplishment of company targets.

3.1.4 Phase 4: Measures for action

Based on the results from previous phases, potential actions are discussed and evaluated in more detail. Depending on the level of pre-existing know how on a specific technology or application, this can cover different stages of the technology life-cycle. Examples for actions that aim at progressing in the technology life-cycle towards the application of resource efficient technologies correspond generally to activities of operational technology management but can also lead to more long term strategic activities. This can include the further development of a certain technology, the acquisition of external knowledge through cooperation or the adaptation of relatively mature technologies to the application in a specific product, service or process.

The major objective of this phase is the classification and prioritisation of different potential activities to implement the prioritised technological options resulting from phase 3. This phase is highly dependant on the strategic orientation and the existing competencies that are available within the specific company.

The communication and further usage of the results are then transferred into the visualised metaphor that represents the technology radar. This model provides a visual representation that translates the most relevant and resource efficient activities into the centre of the radar system, integrating priorities from different areas (see figure 2).

![Figure 2: Exemplary “Resource Efficiency Technology Radar”](image)
This assists in gaining an overview of the timeframe in which each technology is ready for market application and the resource efficiency potential in the context of the company in question. The information can be further integrated in the development of more specific technology, product or market roadmaps for the specific company.

4 Conclusions

This article outlines the results from the author’s current research and industry consulting projects in the field of resource efficiency orientated technology management. The results and approaches presented here are based on the adoption of different existing and new (further) developed methods as well as the in-depth involvement of experts. The designed methods include technology management as well as environmental impact assessment approaches. They were developed to assist companies in dealing with typical technology management related tasks such as the assessment of technological trends and opportunities according to the resource efficiency of e.g. their products and processes.

It has been shown, that a number of technologies, products and strategies are of relevance to increase resource efficiency. However, specific resource efficiency potentials have still to be analysed in on-going research activities and industry application cases. For the field of nanotechnology, it was shown that, while much development in this field is still under way, many results from research for new technologies are already being applied in industry, leading to practical resource savings. Some solutions are already applied, but lack broad application, mainly because of a lack of knowledge concerning their full potential or implementation methodologies.

Practical examples show that higher resource efficiency can be achieved in many cases. However, adequate technologies need to be identified and the specific technology of interest needs always to be thoroughly understood and the resource efficiency potential of its application be assessed. The described methods assist companies to do so and qualify to implement possible approaches into practice. This may lead to strategic advantages and the realization of saving potentials along the value chain. In the end the results and applications that have been outlined should help foster sustainable growth of companies by supporting decision making about the selection of resource efficient technological solutions.

In general, the subject of resource efficiency will further increase in its importance innovation and technology management - considering the growing global demand for raw materials and other natural resources due to the rapid growth of emerging markets.

5 REFERENCES


The Role of Innovation for Energy Transition


CHALLENGES WITHIN THE TRANSITION OF ENERGY SYSTEMS
Introduction

$\text{CO}_2$ and other emissions climate change are largely caused by the way we produce, distribute and consume energy. The trend seems to lead towards catastrophe. Worldwide awareness of this problem is growing and a majority of people are of the opinion that this trend needs to be reversed.

The International Energy Agency (IEA) is a major opinion leader. It was created in 1974 by the Organization for Economic Co-operation and Development (OECD) as an answer to the threat from the Organization of the Petroleum Exporting Countries (OPEC) ("oil shock"). Its main task was and still is to safeguard the energy supply in OECD countries at acceptable costs.

During the creation of the IEA it was already clear that the IEA had to concentrate on the improvement of energy efficiency and renewable energy technologies if it was to find solutions that would decrease the dependency on energy imports. Thus, in 1975 the Standing Committee on Research and Technology (CERT) was created with the mandate to launch international Research, Development, and Deployment (RD&D) -programs and to propose measures for technical improvements in the energy sector.

Standing Committee on Research and Technology (CERT)

At the moment 28 Countries (mostly OECD members) of the IEA have voting rights. In addition the European Commission acts as an active observer and some emerging Non-Member Countries are also actively participating. The collaboration is supported by a legally binding Framework Agreement.

Thereby, CERT has a defined strategy that is revised every five years. The term of the current strategy ends in 2011. It contains the following main elements:

- **Vision:** “Technology will have an increasingly decisive impact on progress in the worldwide quest for a globally clean, clever and competitive energy future.”

- **Mission:** “To maximise energy technology’s impact by optimizing international collaborative RD&D and deployment, by initiating timely technology assessment, analysis and scenarios, by engaging non IEA countries and by delivering policy guidance that will make a difference. A key role of the CERT is to provide leadership for the Working Parties, Expert Groups and Implementing Agreements in the IEA energy technology network, to help them shape work programmes that address current energy issues productively, to support their efforts, regularly review coverage of mandates and suggest new efforts when needed.”
The five Objectives of CERT are:

- Leadership and dialogue to support the various actors
- Stronger focus on the role of technology policy
- Frequent, effective communication to policy makers of messages and perspectives extracted from analysis
- More fruitful liaison within the IEA family
- More vigorous collaboration with non-IEA countries

All these objectives have to be considered when thinking about future activities.

The CERT Organization

The CERT Organization with its Energy Technology Network is a large organization with over 6000 participants from IEA member and non-member countries. The “hands-on” RD&D work is done in the over 40 Implementing Agreements (IAs) and several Expert Groups. In addition internationally recognized energy technology analysis work is done by experts in the IEA Secretariat.

In order to manage the CERT Organization, a hierarchical organization was implemented (Fig.: 1):

- Each implementing Agreement is an autonomous entity with an Executive Committee leading the work. A contract with the CERT regulates the relationship under the umbrella of the IEA. Normally all five years this contract is revised and extended for an other term of five years.
- Industry and Non-member Countries can participate in the implementing Agreements as Contracting Parties, Sponsors or Observers.
- Implementing Agreements are grouped under sectors and overviewed by Working Parties. The Working Parties report to the CERT.
- Some specialised Expert Groups and implementing Agreements report directly to the CERT.
As with the CERT, in Working Parties and Expert Groups all IEA Member Countries are represented by at least one Delegate with voting right. The European Commission and Non-member Countries can participate as observers.

The IEA Secretariat is present in all entities to support the process and to guarantee the link to the Secretariat.

**IEA Collaborative RD&D and Dissemination**

The IEA collaborative international Research, Development, and Deployment RD&D is active in a wide range of technologies in many industrial sectors:

- Buildings (Retrofit, Heating/Cooling, Space Planning)
- Electric Appliances
- Transport (Motor Fuel, Drive Train, Vehicles, Behaviour)
- Industrial Processes
- Efficiency in Fossil Fuel Production and Power Generation (Oil, Gas, Coal, CCS)
- Renewable Energies
- Nuclear Fusion
- Electric Grids (Intelligence, Storage, DSM)
- Modelling (MARKAL)
- Information Centres, R&D Data

**Considerations for CERT’s Strategy 2012-16**

The CERT has started with the process of preparing a new strategy for the period 2012 to 2016. Business as usual in a rapidly changing world is to be avoided by all means. Here, the following considerations should take into account:

- The world changes occurred in the last five years
- Changes (if any) in spirit and style (Governing Board (GB), other Standing Committees, Secretariat)
- CERT acts on behalf of the Governing Board, but likewise it acts as ambassador for the autonomous implementing Agreements and Expert Groups. In such a large Network the internal communication is important, but often even more difficult than external communication due to hierarchical structure where members first concern is to satisfy the level above rather than work with others on the same level.
- The roles and strategies of the Working Parties and Expert Groups who should receive more decision power.

**A radically changed environment**

The world around us has radically changed and is going to change even further in the future. Our focus has to be the change of political awareness and willingness. Some challenging facts include:

- Non-OECD countries will account for 87% of the increase in global demand between 2006 and 2030, driven largely by China and India. The cooperation with Non-member Countries has gained in importance and will be key in the near future.
The shattered world economy makes new investments difficult. Immediate needs for the BLUE Map Scenario (minus 50% CO₂-emissions by 2050) are over 10 Trill $. These are very large numbers.

Instead of rigorous funding decisions, the G8, G20 and IEA Ministerial Meeting launch new initiatives with unclear budget commitments. This leads to a general and dangerous frustration among scientists who, in their transnational thinking, are faced with national policies poisoned by election and re-election activities.

New competing initiatives are created by the same Ministers responsible for the IEA, such as IPEEC (energy efficiency) and IRENA (renewable energies). These initiatives compete with the IEA for funds and human resources. The newest initiative in the process of creation is the International Low-carbon Energy Technology Partnership (ILCETP).

**World Energy Outlook, Technology Perspectives and Roadmaps**

The following three periodic publications of the IEA have gained international fame in the recent years:

- The World Energy Outlook (WEO) is the classical best-seller
- The Energy Technology Perspectives (ETP, since 2006) report has joined the WEO as a best-sellers
- The Roadmaps for various technologies (initiated by the G8 in 2008)

For scientists the Energy Technology Perspectives and the Roadmaps are valuable documents for the choice of focus and the formulation of technology policy proposals.

**Energy Technology Perspective ETP2010**

In the 2008 version of the Energy Technology Perspectives, the IEA called for an Energy Technology Revolution to meet our climate change goals. In our newest edition of ETP (ETP 2010 launched in August) we look at whether we see signs of this transformation happening. The book outlines technologies that are needed and when and where they should be deployed. It also looks at the costs and benefits of this transition and the policies that are needed to make it a reality.

Tackling climate change and enhancing energy security are two central challenges we face in the near and longer future. In the ETP2010 Baseline scenario, which assumes that no new policies are implemented, CO₂ emissions double from current levels by 2050, oil and gas prices are high, and energy security concerns increase as imports rise (Fig.: 2). This scenario is clearly unsustainable and we must act now to move onto a new trajectory.
Policies for Future Energy Systems

Figure 2: Global CO₂ emissions double in the Baseline, but in the BLUE Map scenario abatement across all sectors reduces emissions to half 2005 levels by 2050.

Our BLUE Map scenario has the target of halving CO₂ emissions in 2050 compared to 2005 levels. In this scenario the long-term global temperature rise will be kept between 2°C to 3°C. This is an extremely challenging goal that requires emissions reductions to be made across all sectors. As said above: 10 Trillion $ are needed as immediate investment!

ETP2010 (Fig.: 3) identifies the least-cost combination of low-carbon energy technologies that can help achieve such a 50% reduction and sets out the policies and other actions that will be necessary. The most important option in both the short and longer-term is improving energy efficiency. Improved energy efficiency in the end-use sectors accounts for 38% of the total emissions reduction in 2050.

Figure 3: Key technologies for reducing global CO₂ emissions. A wide range of technologies will be necessary to reduce energy-related CO₂ emissions substantially.
In addition, decarbonising the power sector will be critical to achieving deep reductions. Renewables, nuclear power and fossil fuels combined with Carbon Dioxide Capture and Storage (CCS) will all have a role to play. Particularly after 2030 we will also need new technologies in the end-use sectors of buildings, transport and industry.

The relative contribution of renewables to emission reduction is smaller than that of CCS, because there already is a large contribution of renewables in the baseline scenario.

Accelerating the spread of low-carbon technologies to non-OECD countries is a critical challenge. Action in non-OECD countries will be key to achieving a halving of emissions by 2050. Two-thirds of emission reductions in the BLUE Map scenario will have to come from non-OECD countries.

Figure 4: World energy-related CO2 emissions abatement by region. In the BLUE Map scenario, most of the reductions in energy-related CO2 emissions are in non-OECD countries.

However, technology transfer is becoming more complex with increasing multi-directional commercial and industrial relationships. Capabilities in some emerging economies, such as China are already improving rapidly.

The IEA believes that a low-carbon economy should be based on market principles. The challenge will be to re-orient existing energy-trade while also building capacity in developing countries.

**Technology policies**

Public RD&D spending must at least double. The analysis shows that it may even need to be as high as five times the current level. A range of different policies will be needed to transform the energy sector. Government outreach and planning on infrastructure has to increase, but individual projects have to be bankable in order to create business-cases and attract private investment. Greater international collaboration, including with the private sector, is needed to accelerate technology development and deployment.

A price on carbon is needed for the market to react, but that on its own it will not be enough to transform our energy systems. Additional policies will be needed to support technology development and deployment. These policies need to be tailored to reflect the different stages of technology development.
Policies for supporting low-carbon technologies

The support of new technologies has to match the level of maturity of a technology. Less mature technologies like CCS and fuel cells need strong government support in the form of R&D funding and then financing of demonstration projects.

A number of countries have successfully supported near-competitive technologies like solar and offshore wind with targeted policies like feed-in tariffs or tax credits (Fig.: 5).

Next, as the technology becomes more competitive and mature in the market, governments should remove technology-specific support and shift to technology neutral support, for example in the form of green certificates or more general carbon trading.

Finally, a number of mature and cost-competitive energy efficiency technologies are not being fully used in the market, due to a lack of consumer awareness or a difficulty in paying higher up-front costs. This requires targeted action to address these non-cost barriers. Addressing human behavior is difficult and tricky, but needed. End-use energy efficiency has to become “en vogue”.

World Energy Outlook, Technology Perspectives and Roadmaps: Basis for decisions

The CERT has to find its way in the rapidly changing environment. In its forthcoming meeting on November 3 and 4 it will discuss the use of Roadmaps for the creation of additional policy. Apart from the money that is missing in today’s world we have to face the self-centred motivation of politicians who want to be re-elected. Therefore, an important problem to solve is: “How do we make the actions we propose more popular?”
For this we have to understand how to influence our own energy technology network.

**Exertion of influence**

The implementing Agreements enlarge their range of influence with outreach-activities in non-member countries. Also they give input to the IEA Secretariat for policy proposals that finally reach the Governing Board and eventually the ministers. However, this is sort of “business as usual” and of little impact.

![Diagram: Exertion of influence](image)

**Figure 6: Exertion of influence.**

Much more effective are the publications of the implementing Agreements and of the Secretariat, because they have an influence on the readers who again are of influence in their national and business environment. Through the publications of the IEA the public opinion may be influenced and thus the voters of government politicians?

Within the CERT we have recognized the importance of communication. A workshop last month showed the weaknesses and strength of the existing communication practice with some hints on how to improve that will be implemented in the near future.

**Conclusion**

Politicians strive to popular with voters in their own country, whereas scientists seek the intellectual recognition of their peers regardless of nationality. Yet Politicians need input from science and are dependent on what scientists publish.

This world needs a strong collaboration among scientists with effective outreach of results. Governments have to understand the importance of demonstration and pilot plants in order to prove the feasibility of new measures. There are never too many meetings of scientists! The sense of solidarity among scientists is of utmost importance for our future.

The CERT is here to foster the international collaboration among scientists and to seek for harmonized standards and policy recommendations. Our collegiality is the basis for finding the right path in future energy technologies and policies.
1 Introduction

In order to comply with the 2°C guard rail, it will be necessary to stabilize the greenhouse gas concentration in the atmosphere at a level below 450ppm CO₂eq. In 2004, the use of fossil energy carriers was the largest source of global greenhouse gas emissions, accounting for 56.6 per cent or 28Gt. To stabilize the atmospheric greenhouse gas concentration between 445 and 490ppm CO₂eq, global greenhouse gas emissions will need to be reduced by 2050 by 50–85 per cent from their level in 2000. Studies of the distribution of emissions reduction commitments among states show that stabilization at 450ppm CO₂eq is feasible if by 2020 the emission rights of industrialized states are 25–40 per cent below the emissions of 1990 and, in tandem, emissions from newly industrializing countries drop substantially below present projections. By the year 2050, the emission rights of industrialized countries will need to be 80–95 per cent below the emissions of 1990, and in all other regions emissions will need to drop substantially compared to projections [IPCC, 2007c]. These targets can be achieved in industrialized countries and in the industrialized regions of emerging economies by means of energy-saving measures and with the help of renewable energies such as biomass. This will require a targeted transformation of energy systems.

2 Transformation Components

The transformation is based on expanding the use of renewable energies in tandem with combined heat and power production (CHP), preventing waste heat in the transport sector, utilizing ambient heat for heat supply, and engaging in energy-saving measures across all sectors.

2.1 Efficiency gains through increased direct electricity generation from solar, hydro and wind sources

Electricity is presently generated largely from fossil energy carriers. The associated conversion generates large amounts of CO₂. In the power plants, most of which are large-scale, only approx. one-third of the energy contained in the fuel can be converted into electricity, while the rest is lost as waste heat insofar as no heat is extracted [BP, 2008]. In contrast, electricity generated directly from hydro, solar and wind sources avoids the waste heat losses of thermal energy conversion and thus contributes decisively to improving energy efficiency (Fig. 1).
With increasing renewable direct generation, the fossil primary energy requirement for electricity production is reduced, and the associated GHG emissions drop in step.

2.2 Efficiency gains through expanded cogeneration

Cogeneration (CHP) helps to improve the utilization of fossil and biogenic fuels and thus to reduce greenhouse gas emissions. The use of waste heat, transported via local or district heat networks, for space or process heat saves energy carriers and thus reduces the primary energy requirement in the heat sector. The share of CHP in energy systems can be increased by tapping the major potential for industrial cogeneration, by carefully planning and siting new cogeneration plants, and vigorously expanding heat networks (Fig. 2).

2.3 Efficiency gains through switching to electromobility

Present mobility systems and the associated transport infrastructure have major inefficiencies: on average, an internal combustion engine only converts 20 per cent of the fossil energy into shaftpower (determined in accordance with the New European Driving Cycle, NEDC). Apart from a small proportion used to heat the interior of the vehicle, the remainder of the energy is lost as ambient waste heat. Drives using electromotors are far more efficient, as these make approx. 80 per cent of the energy stored (in the form of electricity) utilizable as mechanical shaftpower.
The 80 per cent efficiency of electric drives (from socket to wheel) arises as follows: in the electric vehicle, electricity is stored in a modern lithium battery by means of a rectifier with an efficiency of up to 95 per cent; when travelling, this is converted back into alternating current via an inverter with the same efficiency, driving an electromotor that has an efficiency of approx. 95 per cent. This makes electric drives four times more efficient than conventional drive systems using internal combustion engines. This factor would still be around 3, if, under optimistic assumptions, internal combustion engines would reach efficiencies of 25 per cent in future and those of electric drives were assumed to be 75 per cent. Even if the higher vehicle weight attributable to the heavy lithium batteries is taken into account, the efficiency improvement factor is still around 2–2.5.

These benefits are not harnessed as yet, however, because the origin of the electricity crucially determines overall efficiency. For instance if this is fossil electricity generated with low efficiency, this negates the energetic benefit of the electric drive. It is only from a certain efficiency of electricity conversion onwards that the use of electromobility becomes technically more efficient than conventional drive systems (Fig. 3).

[Figure 3: Comparison of the efficiencies of fossil of biogenic fuel use in vehicles with internal combustion motors and in electric vehicles. In vehicles with internal combustion motors, approx. one-fifth of the chemical energy filled in the tank is converted into mechanical shaftpower. In vehicles using electric drives, up to 80% of the “filled” electrical energy can be converted into mechanical propulsion. Source: WBGU.]

This is illustrated by combining the efficiency of conventional electricity generation of 38 per cent as shown in Figure 1 with the efficiency of an electric vehicle of 80 per cent: the overall efficiency is then merely a good 30 per cent, which is only slightly above that of conventional drive systems. If, however, the heat is utilized by means of CHP, delivering a power generation efficiency of 80 per cent, the fuel efficiency of electromobility becomes greater than that of internal combustion vehicles in all configurations. Thus, only a combination of electric drives with directly generated renewable electricity from solar, hydro and wind sources fully taps the efficiency potential of electromobility (Fig. 4).
Electromobility delivers further benefits compared to conventional compulsion systems: the thermal conversion process does not take place in the vehicle, but in a stationary system. This makes it possible not only to utilize waste heat, but also to sequester CO₂. Moreover, it resolves particulates issues and mitigates noise pollution. Electromobility also provides potential benefits for energy generators and transmission system operators. It represents an energy store that is available for 90 per cent of the day (non-driving times of vehicles), which, by means of suitable information and communication technologies, can be integrated and used to balance fluctuating feed-in from renewable sources. The prevention of conversion losses in internal combustion motors and the deployment of directly generated electricity in electric vehicles thus present a major efficiency potential in the transport sector. Electromobility systems in which the electricity utilized comes from renewable sources are therefore a key component of the transformation of energy systems towards sustainability.

The above findings apply mainly to road transport, which has the largest share of energy consumption in the transport sector. Broad-scale deployment of electric vehicles, however, can only be realized over longer periods (Fig. 5).
With the exception of hybrid cars, electric drives for series vehicles are still at the development stage. The battery, which must store large amounts of energy yet also be light and have a long service life, is a neuralgic point. Nonetheless, electric vehicles with ranges of 100–200km are already being manufactured today, and many carmakers plan to include electric and hybrid vehicles in their fleets [Engel, 2007]. In the medium term, it can even be expected that electric drives will be used in heavy goods vehicles.

In aviation, however, there is presently no alternative to liquid, carbon-based energy carriers. While the situation is similar in shipping, here new propulsion systems such as controllable kites have the potential to reduce the fuel consumption of a ship by 10–50 per cent. Prototypes are already in use [Skysails, 2008]. Rail transport already runs mainly on electricity in numerous countries and uses a dedicated electric grid [Oeding and Oswald, 2004; DB, 2008]. In Austria, for instance, the share of hydropower in railway electricity supply already amounted to 89 per cent in 2007 [ÖBB, 2008]. If it should become possible in future to no longer consume mineral oil in passenger cars thanks to electric drives, then the oil can be deployed in long-transport, in aviation and in shipping until alternatives are found.

### 2.4 Efficiency gains through using electric heat pumps for heat supply

Conventional oil- and gas-fired heating systems have efficiencies of 70–110 per cent based on the net calorific value (condensing boiler technology; BHD, 2008; DIN, 1990). Through direct combustion in oil- and gas-fired heating systems, the energy stored can be converted to 100 per cent into heat and almost to 100 per cent into useful heat (hot water, space heat etc.). If electricity is used in an electric heat pump, that raises the available ambient heat to a suitable level and renders it utilizable, substantially more heat can be supplied. The quotient between the utilizable heat output and the electrical energy consumed in the compressor is termed the coefficient of performance, and is determined according to defined conditions in various standards such as EN 14511 (DIN, 2008a, b; VDI, 2008). Assuming that electric heat pumps have an average performance coefficient of 3.5, an input of 1kWh electricity can deliver 3.5kWh heat, of which 2.5kWh come from the ambient heat [Baumann et al., 2006]. This value is especially likely to be achieved if heat pumps are linked to geothermal systems. Under favourable conditions heat pumps can then achieve high annual performance factors. As in the field of electromobility, the origin of the electricity or the efficiency of power generation is decisive. Only from a certain power plant efficiency onwards is the use of electric heat pumps more favourable than the direct thermal use of fuel, as illustrated by the following example.

The present generation mix, with its efficiency of 30–35 per cent, can generate approx. 0.30kWh electricity from 1kWh fossil or biogenic energy. With the performance coefficient assumed here, the electric heat pump can use this electricity to deliver at most 3.5 times more heat, i.e. in our example approx. 1kWh heat. Under such circumstances the use of electric heat pumps is pointless, as the direct combustion of fossil or biogenic fuel would deliver the same utility. However, the useful heat ratio rises to approx. 200 per cent if the electricity is generated in combined-cycle power plants with efficiencies around 60 per cent, and even climbs to 350 per cent if the electricity was generated directly from solar, hydro or wind sources. It follows that the energy efficiency of electric heat pumps is best harnessed by using directly generated electricity (Figs. 6 and 7). Thermal heat storage systems can decouple electricity demand from heat demand. This allows efficient load management; for instance, in periods of high wind power generation, the surplus electricity can be stored in this manner. The observed trend towards an increasingly larger proportion of direct generation from renewable sources will in future substantially improve the overall energetic efficiency of electric heat pumps.
Figure 6: Efficiency gain through using ambient heat by means of heat pumps running on renewable electricity. Source: WBGU.

Figure 7: Heat sector transformation: through CHP expansion and the greater use of electric heat pumps, process and space heat demand can be met entirely in future. Source: WBGU.

Broad-scale introduction of heat pumps greatly reduces the consumption of fossil and biogenic fuels in the heat sector. In combination with waste heat from CHP, the fossil primary energy requirement and thus GHG emissions in the heat sector can be reduced greatly; in the ideal case, directly combusted energy carriers can be substituted. Space heat, hot water heating and a part of process heat can all be supplied in this manner. A further part of process heat demand can be met by renewable electricity.

2.5 Efficiency gains through energy conversion measures

There are many ways to make the use of energy more efficient – i.e. to reduce energy requirement while delivering the same level of utility. Such options are available in all energy sectors. This is highly evident in the heat sector: thermal insulation, meeting the ‘passive house’ standard in the ideal case, can greatly reduce the energy required for space heating. Improved space heating systems, cooking stoves and hot water production systems are further examples.
In the electricity sector, too, there are many options. For example, in industrial processes compressed air is often used highly inefficiently. Installing improved sealings and exchanging leaky components can save electricity consumed in compressors. Savings in lighting are a further example. An industrialized country such as Germany only consumes 5 per cent of electricity consumption for lighting; however, 95 per cent of this is dissipated as waste heat when used in conventional incandescent lamps. If in each of the 39 million German households 75 watt standard incandescent lamps were replaced by 15 watt compact fluorescent lamps, which have the same light output, 2.3GW generating capacity, which translates into two large-scale power plants, would theoretically no longer be needed during the period of lighting demand. All household appliances (refrigerators and freezers, stoves etc.), lighting devices (LED technology) and industrial processes (electric drives, power electronics, etc.) could be designed so as to be more efficient, meeting the same purpose with less electricity consumption. Switching off stand-by circuits by installing switchable sockets, or even banning stand-by, is a further measure that would promote energy efficiency.

In the transport sector, the energy consumption of all aircraft and vehicles can be reduced by improving their aerodynamics and reducing their weight or rolling resistance. This goal can also be furthered by means of socio-economic and organizational measures such as improved local public transport systems, better capacity utilization of buses, trains and aircraft, or improved traffic flow organization. The period considered decisively determines all quantitative savings potentials.

3 Conclusion: Transformation energy systems by combining the components

If the five components set out above are combined, the fossil and nuclear primary energy requirement of an industrialized country can be reduced by more than 80 per cent, and energy-related GHG emissions curbed accordingly. This corresponds to the reduction obligations that may result from a newly negotiated Kyoto Protocol for Annex I countries such as Germany. In a transformed energy system, GHG emissions of quantitative relevance only arise from fossil and biogenic electricity generation in CHP systems and in highly efficient combined-cycle power plants. The very low emissions from wind, hydro and solar energy are negligible in comparison.

These five components boost efficiency in an energy system that need not be a distant vision, but is in fact a route that can be taken with present technology (Fig. 8).
Figure 8: Energy system transformation – the example of Germany, an industrialized country: five key components can deliver both energy and climate efficiency. Source: WBGU using data from BMWi, 2008.

References

WBGU Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen.


A New Future for District Energy Systems

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Abstract

District energy (DE) is a means for delivering heat and/or cooling to multiple buildings from a central energy centre. DE spans a wide variety of scheme sizes, from a small group of buildings in the same neighbourhood through to city-wide schemes comprising thousands of connected buildings.

The use of DE enables whole communities to benefit from low and zero carbon energy sources, including those which cannot easily be installed at the individual building level. It also confers fuel flexibility: the energy centre may comprise a variety of heat sources.

Those countries which have already developed a mature DE industry have seen the penetration, particularly of district heating, grow to a high percentage of the total existing buildings-related heat demand. This paper focuses on new opportunities and challenges for DE arising from future highly energy efficient new buildings and the increasing role of renewables:

- New and future buildings offer greater ease of installation for DE infrastructure from the outset but require substantially reduced heat demand.

- New techniques are appearing for the DE technology itself. These include new pipe configurations to reduce heat losses and lower priced plastic pipe technologies that can be deployed in the case of low temperature systems.

- The fuel flexibility of DE infrastructure lends itself to the integration of thermal renewable technologies that are crucial to the overall reduction of carbon emissions: biomass, solar thermal, heat pumps, deep geothermal.

- For communities of the future, integration of systems and technologies will be of paramount importance. DE provides flexibility to make use of very low grade energy and is already a low exergy approach, routinely recycling heat that would be thrown away. Low and very low temperature networks allow different sources of heat (eg water lying in disused mineshafts) to increase flexibility in matching demand with locally available heat sources.
1 What is district energy?

District energy is a means for delivering heat and/or cooling to multiple buildings from a central source. The countries that have developed this technology tend to have been those in which heating demands are of most concern, so that district heating (DH) is prevalent. However, even Northern cities have significant cooling demands, so that district cooling (DC) is a growing market.

There are three basic parts to a DH scheme (see figure 1 left): an energy centre containing the heat source(s), a hydraulic interface unit (HIU) e.g. heat exchangers and a network of pipes to connect them.

The energy centre houses the heating plant which can include a range of technologies and fuels e.g. gas boilers, biomass boilers and combined heat and power (CHP). Hot water from the energy centre is pumped through the pipe network to the individual buildings.

Figure 1 right shows for a dwelling, heat conveyed via the HIU to central heating radiators and hot water taps. Modern applications of DH can offer lower running costs and therefore lower heating bills for the customers. Furthermore occupant safety is enhanced because DH removes the need for gas-fired appliances within dwellings.

DH schemes involve major capital investment and the heat distribution network is one of the most expensive elements. Therefore, in order to maximise the heat sales per unit of capital invested, (i.e. small pipe length per unit heat delivered), DH is best installed in areas with a high concentration of heat demand.

Where existing DH networks exist the best solution for any new developments will almost certainly be to negotiate a connection to the network. Similarly, where new DH schemes are being developed for new build developments, there will be benefit for all if any nearby existing buildings can also be connected.

Figure 1: (left) The principles of DH, (right) The hydraulic interface unit. (Source: BRE)
2 District energy for new and future buildings

New buildings are generally more energy efficient than existing buildings. This trend will continue in the future due to the strengthening of the energy efficiency requirements that buildings will have to comply with.

An immediate effect of the strengthening in the energy efficiency standards for buildings is the reduction in the amount of energy that would be required to heat future buildings. This means that:

- Heating requirements are increasingly dominated by domestic hot water (DHW) rather than space heating. Figure 2 demonstrates this with three different energy efficiency scenarios for dwellings: base case, low energy and PassivHaus
- The annual heat profile will be flattened, see Figure 3: a year-round base heat load will remain but winter heating is much reduced.

![Figure 2: Annual space heating and domestic hot water requirements of new and future buildings.](image1)

![Figure 3: Monthly space heating and domestic hot water requirements of new and future buildings.](image2)

Work carried out within Annex VIII of the IEA District Heating & Cooling (IEA DHC) programme\(^1\), and further work currently progressing within the current Annex IX examines the role of DE in new and future buildings.

Within this work, and through associated research at BRE, modelling has been carried out of three representative UK new-build residential developments with different dwelling densities: detached house development, mixed residential development and blocks of flats.

Figures 4 and 5 below show the relative heat distribution losses, from which the following is concluded:

- For the same dwelling density, moving from the (new-build) base case dwelling to PassivHaus standard could double the relative heat distribution losses, although this is more pronounced for lower dwelling density developments
- The greater the dwelling density the less sensitive the relative heat distribution loss is to linear heat density
- Despite the lower heat demand of new and future buildings, the heat distribution loss of well-designed DH schemes supplying high dwelling density developments, such as blocks of flats, is small relative to the total amount of heat delivered by the heat network.

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\(^1\) [www.iea-dhc.org](http://www.iea-dhc.org)
3 Reducing heat distribution losses

Reduction of heat distribution losses is an important aspect of improving DH network performance, and has therefore been investigated mainly in countries with a history of DH. The IEA DHC programme has and is undertaking research looking at the use of DH to supply heat to areas of low heat demand density ([Zinko et al, 2008] for instance)

In order to reduce the relative heat distribution losses one can either:

- increase the total heat delivered by the heat network, thereby increasing the heat demand density. There are only limited ways in which this can be sensibly achieved, but one possibility is to shift some of the electricity demand of washing machines to district heating ([Zinko et al, 2008] and [Persson et al, 2007])
- reduce the absolute heat distribution losses by:
  - using higher performance pipes
  - using smaller pipe diameters, e.g. through the use of local hot water storage or booster pumps
  - reducing the heat network operating temperature

3.1 Use of high performance pipes

Traditionally, DH networks have used pre-insulated single pipe systems. However, heat distribution losses can be reduced further through the use of higher performance pipes such as twin pipes ([Zinko et al, 2008] and [Olsen et al, 2008] for example).

Modelling has been undertaken to estimate the effect that using twin pipes has in reducing heat distribution losses relative to the use of single pipe systems. The results indicate that pre-insulated twin pipe systems can reduce heat distribution losses by 20-30% relative to pre-insulated single pipe systems.

This is in line with the findings reported in [Zinko et al, 2008] which suggested that heat distribution losses had been reduced by 37% in twin pipe systems relative to single pipe systems. [Zinko et al, 2008] concluded that single pipe systems should not be used in DH schemes supplying areas of low heat demand density.
3.2 Use of smaller diameter pipes

Using smaller diameter pipes can reduce the absolute heat losses as the pipe heat transfer surface with the ground is reduced. The use of smaller pipe diameters can be achieved by the adoption of alternative network design strategies ([Zinko et al, 2008] for example):

- Heat networks with higher temperature differences between flow and return would require smaller flow rates to deliver a certain amount of heat.
- If the peak heat demand that the heat network has to supply is reduced, the required pipe diameter could be reduced. In energy efficient dwellings, the peak heat demand is dominated by DHW. Localised hot water storage at the building level could be used to flatten the demand profile and, thus, reduce peak demand ([Olsen et al, 2008]). Another option would be a buffer tank on the primary side of the heat exchanger.

Smaller diameter service pipes can be used alongside booster pumps. In periods of high heat demand, the booster pump (installed at the customer heat station), is used to increase flow.

3.3 Lowering flow and return heat network temperatures

Heat distribution losses can also be reduced by lowering the flow and return temperatures.

In order to enable the use of low temperature DH systems a heat distribution system able to deliver useful heat at lower temperatures has to be used. This may be achieved, for example, by means of bigger than usual radiators or under floor heating and in-wall systems. Additionally, the heating emitters and controls and the hydraulic interface between the heat network and the building heating systems will have to be suitably designed, in order to minimise the heat network return temperature. ([Dittmann et al 2008]) suggested that a means to further reduce the return temperature of the heat would be to connect customers to the return pipes. In this situation, it is likely that the return temperatures are suitable for space heating but not for domestic hot water provision. This might be solved by using other supplementary energy sources at the building level.

It is important to bear in mind that if the return temperature is kept constant, lowering the supply temperature will require an increase in the network mass flow to deliver a certain amount of heat. This will lead to higher flow velocities and bigger pressure losses, increasing the demand for pumping energy.

4 LowEx district energy

4.1 District energy is LowEx

A central part of the LowEx concept is to make use of low grade and/or waste energy. The lower the quality of energy that we are able to still use, the more we preserve high quality energy for other uses. DH is already a low exergy approach in that sense. If networks are not solely operated by burning fossil fuels for heating purposes only, DH systems routinely recycle heat that would otherwise be thrown away: heat derived from industrial waste, incinerated waste, solar thermal, from geothermal power plants as well the more familiar fossil-fuelled CHP.

For thermal power generation, use of waste heat is often a prerequisite for its financial viability: While the construction of the network needs large investments, heat sales add considerable value. While the efficiency of a CHP plant is smaller than that of a Combined Cycle Power plant optimised for electricity production, most of the otherwise wasted low value energy can be used for heating.
4.2 Low and very low temperature networks

District Energy networks are based on the principle of transporting energy from its source to a number of users. The higher the energy density of the energy carrier, the smaller is the needed mass flow and the further it is economically viable to pump it. DH has thus traditionally been operated at temperatures exceeding 100°C, although lower temperature systems often using plastic pipes (for temperatures lower than 90°C) have also been developed. The possibility of lower temperature systems has recently attracted attention; consequently Annex X of the IEA DHC research programme seeks to examine the potential of lowering supply and return temperatures (e.g. 50°C/20°C; 70/40; 75/30).

Even lower supply temperatures provide the possibility to extend still further DH’s environmental potential by accessing heat from sources formerly considered as with little to no value like minewater or ground heat. It is important though to combine these networks with appropriate measures on a building level, e.g. well-insulated fabric and underfloor and in-wall heating.

These emerging alternatives allow the DH network to be adapted to demand and locally available resources. In an urban context with for example industrial waste heat at 100+ºC, high supply temperatures are preferably used. However, if ground heat is the major source available lower flow temperatures may be appropriate, whether with centralised or decentralised heat pumps. As the temperature is much closer to the ambient temperature, the heat loss from the pipes is much smaller. Using plastic pipes for low temperature networks has the potential to decrease the capital cost and therefore economic viability considerably.

Figure 6: Andermatt Alpine Destination (CH) with ground heat exchanger field (left), very low temperature network and decentralised energy centres with heat pumps. Conventional wood-fuelled DH network for existing buildings and peak-loads. (Source: Amstein + Walthert AG)

These systems access new sources and provide more flexibility in the design of the system. For a newly constructed tourist resort in Andermatt for example (see Figure 6), a very low temperature loop at <10°C serves as the central heating AND cooling network to which a variety of heating sources are connected: fields of ground heat boreholes, ground water heat exchangers, waste heat recovery, exhaust air heat recovery and the option of hot tunnel excess water. Heat pumps are placed in
decentralised energy centres where they lift the temperature from the supply pipe to usage level. The return flow is used for free cooling, with the borehole fields being used as a seasonal buffer. A wood pellet plant is built to heat existing buildings with the need of higher supply temperatures. A parallel DH network at an appropriate temperature delivers heat into the same energy centres with heat exchangers, to be used for peak loads. Electricity obtained exclusively from renewable resources ensures CO₂-neutral energy supply.

5 Integrating renewable energy into district energy systems

DE networks can play an important part in the gradual transition towards a low carbon future, as a system that brings fuel flexibility to adapt to and integrate renewable technologies as they come along. Technologies like gas-fired CHP are likely to remain important for some time to come, in using fossil fuels in a more efficient way, and acting as a catalyst to the expansion of DH infrastructure and reducing carbon emissions now. Such a network can equally well use heat from biomass-fired plant, solar thermal or even in the future a hydrogen fuel cell.

As the characteristics of each renewable energy system (RES) are different, so are the benefits of integrating one into a DH network: in a densely built area for example, supply and storage of sufficient fuel for a number of individual biomass boilers can pose a problem. One central energy station at a suitable place solves not only that problem but offers economies of scale for sales and transport issues. The space for solar thermal systems or ground source heat exchangers to supply high-rise apartment buildings with heat may well exceed their own footprints. A DH network can be used to transport the heat from nearby energy-harvesting fields with less intense energy demands to the high-demand area.

Thermal storage has an important role in matching supply and demand dynamics, especially with stochastic heat production of some RES like solar thermal systems and prominent peak loads of daily use. Networks lead to a slight levelling of demand, especially in mixed-use areas, capping peak loads and allowing RES to be sized more cost-effectively. While individual storage tanks in buildings are well established for regular charging and discharging, storage opportunities at a larger scale seem to be more cost-effective for seasonal storage.

Within Annex IX of the IEA DHC research programme, work is proceeding that examines the way in which a heat network could function in the future through connected buildings being able to receive or donate energy.

In particular, the work focuses on future buildings featuring very low heat loss factor, long cool-down time constant, passive and active solar, active thermal storage and sophisticated energy management. Due to their exceptionally low energy consumption it may appear impractical to connect them to a DE system. However, these buildings are capable of peak load shedding, off-peak charging of thermal storage and can act as a source of distributed thermal energy to the DE network when they have surplus energy.

The objective of the project is to establish the most cost-effective interface configurations and control strategies to maximise the benefits to both the DE utility and the building owner. The conclusions will be reported at the 2011 End-of-Annex seminar for the IEA District Heating & Cooling research programme.

DE networks provide the possibility to integrate several different RES plants and technologies. This diversification of energy sources leads to increased energy security and supply resilience. While there is a strong potential for the physical integration of RE in networks, there are still a lot of uncertainties on how best to integrate them. The next Annex X of the IEA DHC programme will continue with this focus.
Conclusions

The following can be concluded:

- Despite the lower heat demand of new and future buildings, heat distribution losses of well-designed DH schemes supplying high dwelling density developments, such as blocks of flats, are small compared with the total heat delivered by the heat network.

- Techniques exist in order to reduce the heat distribution losses of a DH network. They include the use of high performance pipes: for pre-insulated twin pipes heat distribution losses can be reduced by 20-30% compared with pre-insulated single pipe systems.

- Other techniques exist that can be used to reduce heat distribution losses, e.g. using smaller diameter pipes with local hot water storage, or using booster pumps installed at the customer heat station.

- DE networks lend themselves to integrating different RES technologies and fuels, increasing energy security and supply resilience. While there is a strong potential for the physical integration of RE in networks, there are still a lot of uncertainties on how best to integrate them. DE networks have a transformative role towards a low carbon future, particularly in combination with CHP plants.

- DE is already a LowEx approach as it routinely recycles heat that would otherwise be thrown away. Using waste heat is often a prerequisite for thermal power stations for its economic viability.

- Low and very low temperature networks allow accessing different sources of heat to increase flexibility in matching demand with locally available heat sources.

References


A new Role of Utilities within Energy Transition

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1 In a nutshell: three reasons for transition of utilities

• Firstly, electricity generation (supply side) is rapidly changing towards decentralised structures mainly due to climate protection and securing energy supply by a higher share of “home-based” technologies.

• Secondly, measures for energy savings on the demand side are strengthened in all private and commercial areas such as building standards / heating, mobility and electric appliances. Utilities are fostering efficient solutions of energy consumption.

• Thirdly, utilities act within an increasingly competition, stakeholder and regulatory impacted environment that demand sustainable energy solutions in terms of economy, ecology and security of supply.

Consequently, for utilities it is vital to further develop innovative solutions in energy supply and demand. Therefore RWE has decided to become greener, more international as well as robust. Shining examples that demonstrate the transition of RWE are the foundations of

RWE Effizienz GmbH – delivering efficiency products to the mass market and

RWE Innogy GmbH – offering fast growing renewable supply solutions.
Both companies contribute to the common goal of sustainable CO₂ reduction!

2 Changes in electricity generation and distribution (supply side)

The value chain of an utility used to be very clear in the past: centralised power stations fed electricity into grids distributing the load unidirectionally to costumers such as private households. Utilities ran power generators according to precisely forecasted demand. Fossil fuels were the dominant source of primary energy.

Power generation is becoming much more diverse nowadays in terms of energy sources, time and volatility of injection. Renewables, especially wind and solar, dominate that still growing volatile supply situation. This development is correlated with power generation units becoming smaller and more flexible than they were decades ago. In addition, cogeneration is coming much more in place for making use of formerly dissipated heat but also for shaving capacity peaks, which matters in times of
volatile renewable energy structures. Utilities must respond to such challenges by decisive innovation and investment leading to “smart grids” including advanced storage technologies.

Grids are being extended by information streams in order to control “intelligent” devices such as electric heat pumps or washing machines running when electricity is less expensive or a charging unit for e-mobility consuming electricity when wind blows and feeding back when peak demand calls for additional load. Micro-CHP, small cogeneration units in private households, are another element of the upcoming smart grids. Many private household will be categorised “prosumers” because of their consumption as well as production function.

RWE Effizienz GmbH was established in order to provide system solutions containing highly efficient and standardised end user products. The company was set up to promote all energy efficiency efforts and energy services within the Group. RWE sees significant potential for business growth in this area, with the additional benefit of improving the company’s environmental scorecard.

3 RWE Effizienz GmbH as spin-off for standardised solutions

RWE pooled its energy-efficiency activities in a new company as part of its reorganisation programme. Headquartered in Dortmund, Germany, RWE Effizienz GmbH began operating on July 1st, 2009. Its product and consulting offerings target private customers, small and medium-sized enterprises, municipalities as well as service partners such as tradesmen and architects. It promotes, among other things, the use of modern electricity meters (so called “Smart Meters”) to improve monitoring of energy consumption as well as computer systems to control residential equipment and appliances (Smart Homes). Its activities also include electric vehicles.

The aim is to create systems for making efficient use of electricity and heating homes marketable. These systems, in forefronts RWE SmartHome, will be designed to enable the user-friendly control of heating, light and household appliances.

Electric vehicles are another promising field of Research & Development we have tapped into. RWE has already begun to set up intelligent infrastructure in Germany. By this undertaking, we aim to build a network of charging stations that will initially cover catchment areas, combined with a billing system, enabling customers to recharge their vehicles quickly and conveniently. We have developed a large share of the required systems ourselves. At present, we are testing them in regional pilot projects with Daimler (Berlin) and Renault (North Rhine-Westphalia).

Last but not least, ongoing effort has been put into informing a large spectrum of people about energy efficiency and realizing economic benefits for RWE at the same time. The domain energiewelt.de provides such a business case where interest for the common good and economic profits meet.

After one year of activities, RWE Efficiency already hired its 100th staff member and is still growing. Many projects and ideas are still in the pipeline – a great basis for future solutions of energy efficiency, yet one challenge remains: all actors shall get involved into processes towards higher efficiency at an early development stage. Putting this challenge into action is most crucial.

Energy efficiency: an important module in the climate protection strategy

RWE believes in energy efficiency as an indispensable prerequisite for more climate protection. Which is why we offer our customers products that promise an economical, modern and responsible way of dealing with energy.

We help to make a piece of the future with the experience and competence of RWE.

Because less consumption is more progress
METHODS AND DESIGN
Exergy Thinking and Thermal Comfort

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1 Introduction

Research on the built environment with the exergetic viewpoint has been grown to the present since early 1990s. In due course, the exergy concept itself was developed and sharpened to a large extent, in order to make it possible to apply in particular to the field of building physics and its related areas such as indoor thermal environmental science.

Exergy analysis of the built environment equipped with space heating and cooling systems articulates how much and where exergy is consumed in the whole process from its supply and consumption to the resultant entropy generation and disposal. Space heating and cooling systems themselves are physical systems at their own right, but their purpose is to control the built environmental condition within a certain range that allows the occupants to be healthy and comfortable with rational ways of exergy consumption.

Physics with respect to the built environment and its technology must be in harmony with human physiology and psychology. In this sense, it is of vital importance to have a better understanding of the human-body as a thermodynamic system at dynamic state from the exergetic viewpoint; this is to deepen our understanding of the built environment, especially with respect to heating and cooling and thereby develop rational heating and cooling systems for the built environment in the future.

This paper first reviews as briefly and easily as possible, without mathematical formality, the fundamentals of thermodynamics, with a focus in particular on how the “thermal energy dispersion” occurs in nature and on what the “consumption” is. In due course, the image of “exergy-entropy process” is explained so as to enrich the image of flow and circulation, which is the key in designing the sustainable built-environment.

A couple of numerical examples of the whole human-body exergy consumption rates for winter and summer conditions in relation to the built environment are given and the essence of the findings are introduced. According to a series of analyses having done so far, there are the minimum values of human-body exergy consumption rate both in winter and in summer and both of them are consistent with the direction towards the development of so-called low-exergy systems for heating and cooling.

2 Exergy Balance Equations in General

Generally speaking, a thermodynamic system to be investigated, whether it is a human body, a building wall, a heat pump or others, is regarded to be surrounded by its environmental space. The whole of the system and the environment is regarded to be the universe. Any working system works feeding on some energy and matter, while at the same time, storing their portions and/or giving off the remainders. In due course, the whole amount of energy is necessarily conserved while on the other hand, an amount of
entropy is necessarily generated. The generated entropy may be stored for a while not to be discarded into the environment, but soon or later it must be discarded.

A portion of energy, whose associated temperature, pressure and chemical potential are in equilibrium with their corresponding values in the environment, has no capability of dispersion. The other portion of energy, which has not yet dispersed, has a capability of dispersion. That is exactly exergy which is the driving agent for the system. As can be seen in the left side of Figure 1, a working system feeds on exergy from a source and dumps the generated entropy, which is proportional to the exergy consumption within the system, into the environment. We call such process “exergy-entropy process” [Shukuya and Hammache 2002; Shukuya 2004].

Exergy balance equation for the system can be set up in a general form as

\[ [\text{Exergy input}] - [\text{Exergy consumed}] = [\text{Exergy stored}] + [\text{Exergy output}] \]  

(1)

In order to set up the detailed form of Eq.(1), we first set up an energy balance equation according to “the law of energy conservation (the 1st law)” and then the corresponding entropy balance equation according to “the law of entropy generation (the 2nd law)”. Extraction of the product of the entropy balance equation and the environmental temperature from the energy balance equation brings about the “exergy” balance equation. The whole procedure is as schematically shown in the right side of Figure 1.

3 The Human-Body Exergy Balance Equation

The thermal exergy balance equation of human body as a two-node model of core and shell is derived as follows by combining the energy and entropy balance equations together with the environmental temperature for exergy calculation, which is outdoor air temperature [Shukuya et al. 2004; 2010].

\[ \text{[Warm exergy generated by metabolism]} \]

+ \[ \text{[Warm/cool and wet/dry exergies of the inhaled humid air]} \]

+ \[ \text{[Warm and wet exergies of the liquid water generated in the core by metabolism]} \]
+ [Warm/cool and wet/dry exergies of the sum of liquid water generated in the shell by metabolism and dry air to let the liquid water disperse] + [Warm/cool radiant exergy absorbed by the whole of skin and clothing surfaces] - [Exergy consumption] = [Warm exergy stored in the core and the shell] + [Warm and wet exergies of the exhaled humid air] + [Warm/cool exergy of the water vapor originating from the sweat and wet/dry exergy of the humid air containing the evaporated water from the sweat] + [Warm/cool radiant exergy discharged from the whole of skin and clothing surfaces] + [Warm/cool exergy transferred by convection from the whole of skin and clothing surfaces into the surrounding air].  

If an overall investigation of the human-body exergy balance is made together with building heating or cooling system’s exergy balance, the environmental temperature to be taken must be the same for both the human body and the heating or cooling system. The first term of eq.(2) is the warm exergy produced as the result of chemical exergy consumption for a variety of cellular activities, mainly for the contraction of muscle tissues, the composition of proteins, and the sustenance of the relative concentrations of various minerals in the body cells.

The exergy-consumption appeared in the last term of the left side of eq.(2) is due to two kinds of dispersion: one is thermal dispersion caused by the temperature difference between the body core, whose temperature is almost constant at 37°C, and the body shell, namely the skin, whose temperature range from 30 to 35°C, and the clothing surface, whose temperature range from 20 to 35°C; the other is dispersion of liquid water into water vapor, in other words, free expansion of water molecules into their surrounding space.

All terms in the right side of eq.(2) except the first term, exergy storage, play important roles respectively in disposing of the generated entropy due to chemical and thermal exergy consumption within the human body. These processes of outgoing exergy flow together with exergy consumption influence very much on human well-being: health and comfort.
Some Numerical Examples and Their Discussion

Two examples of the whole exergy balance of a human body in a winter condition of outdoor air temperature and relative humidity of 0°C and 40% are shown in Figure 2 [Shukuya et al. 2010]. The twin-bar graphs to be discussed here are consistent with the expression given in eq.(2), once the term of “exergy consumed” is moved to the right side of the equation. The indoor operative temperature in these two examples is assumed to be 22°C equal to each other, but the combination of mean radiant temperature and surrounding air temperature are different from each other: they are 19°C; 25°C or 25°C; 19°C.

Although the exergy input consists of five components as shown in eq.(2), three components associated with the inhaled humid air and liquid water emerged in the core and in the shell are much smaller than the other two components in winter conditions. Therefore they are included in the portion of “Humid air + Water”. Since the exergy stored is also very small compared to the exergy consumption and others, it is not apparent in the bars shown in Figure 2.

The exergy-consumption rate amounts to 20 to 30 % of the input exergy rate and they are different from each other in the two cases. The smaller is in the case of the mean radiant temperature higher than the surrounding air temperature.

![Figure 2: Two examples of the whole human-body exergy balance under a typical winter condition, outdoor air temperature and relative humidity of 0°C and 40%, respectively. Exergy stored is negligibly small so that it is not shown in these graphs.](image-url)
The sum of relative rates of warm radiant exergy emission and convective warm exergy transfer is very large in the case of the mean radiant temperature higher than the surrounding air temperature. This is due to the higher mean radiant temperature resulting in the higher average temperature of the skin and clothing surfaces and leads to a smaller exergy consumption rate. Such a condition must relate to providing the human body with a higher level of thermal comfort.

**Figure 3** shows two other examples of the whole human-body exergy balance under a typical summer condition in a hot and humid condition, outdoor air temperature and relative humidity of 33°C and 60%, respectively [Shukuya et al. 2010]. How to read these twin-bar graphs are exactly the same as Figure 2. The twin-bar graph at the top shows a case of radiant cooling together with natural ventilation and that at the bottom a case of mechanical air cooling. For the former, the surrounding air temperature, humidity and air movement are assumed to be 30°C; 65% and 0.3 m/s, respectively, and for the latter, 26°C; 50%, and 0.1 m/s, respectively. For both cases, the mean radiant temperature is assumed to be 27°C.

The profiles of exergy balance in summer cases are quite different from those in winter cases shown in Figure 2. There are four apparent differences. One is that the absolute values of exergy input rate in summer are much smaller than those in winter; this is because of a small temperature difference between indoors and outdoors in summer.

![Figure 3](image-url)
The second is that the relative rates of wet exergy contained by liquid water, especially in the body-shell rather than in the body-core, are much larger than those in winter due to more sweat secretion in the case of radiative cooling and also due to dryness of room air in the case of convective cooling. The third is that there is cool exergy given by convection in addition to radiation, though its relative magnitude is smaller than that of cool radiant exergy. The fourth is that the relative rates of exergy consumption are very large compared to the output exergy rate.

All of the wet exergy of liquid water given inside the human body and the cool radiant exergy coming onto the human body in addition to cool exergy transferred by convection are to let the inevitable metabolic “warm” exergy be consumed in order to maintain the human body within a desirable thermally-well-being state. The relative magnitude of the output exergy rates is very small in comparison to exergy consumption, but it does not imply that it is less important; they are essential in disposing of the generated entropy inside the human body due to exergy consumption of “warm” and “wet”/“cool” exergies. In other words, the output exergy rates are small, since they are accompanied by a lot of entropy to be discarded into the environmental space.

A series of our recent studies [Iwamatsu et al. 2008; Shukuya et al. 2010] shows that there seems to be a set of mean radiant temperature and air-current velocity giving the lowest human-body exergy consumption rate. Figure 4 shows a relationship between the human-body exergy consumption rate, whose unit is W/m² (body surface), and the combination of mean radiant temperature and air movement under a summer condition (33ºC; 60%rh) in the case of radiative cooling combined with natural ventilation. Here we assumed that room air temperature and relative humidity of 30 ºC and 65%, respectively. Such a room air condition during daytime at outdoor air temperature and relative humidity of 33 ºC and 60% can be realized by natural ventilation together with radiative cooling wall or ceiling panels, thermally-activated building-envelope system, or with the cool storage by floor, walls and ceiling due to nocturnal ventilation by either an active system or a passive system made during the previous days [Shukuya 2007].

A combination of mean radiant temperature controlled lower than 30 ºC, say in the range of 28 to 29 ºC, and air movement exceeding 0.2 m/s provides the human body with his/her lowest exergy consumption rate. The lowest exergy-consumption rate turns out to be about 2 W/m² for the air movement smaller than 0.2 m/s and even a little less than 2 W/m² for the air movement over 0.2 m/s.
In a naturally ventilated room space, almost random natural fluctuation of soft air movement, namely breeze, brings about pleasant coolness, which is called “Suzushisa” in Japanese; this is rather a dynamic condition different from static neutrality of neither hot nor cold. A dashed line represents the condition at skin-wettedness of 0.25, over which it might hardly be tolerant. It is interesting that the lowest values of exergy-consumption rate lie just below this line.

The human-body lowest exergy consumption rate can also be given in the case of convective cooling as shown in Figure 5. In this example, room air temperature and relative humidity are assumed to be 26 °C; 50%rh. The lowest exergy-consumption rate of 2.3 W/m² or less can be found for the range of 0.3 to 0.4 m/s of air movement with mean radiant temperature of about 26 °C, though such a rather high air velocity around the human body in a mechanically air-conditioned space must result in discomfort. Therefore, the air current for mechanical cooling mainly by the use convection should be reduced to the air movement of 0.15 m/s at the highest.

If the air movement is assumed to be 0.1 m/s for this reason, the lowest exergy consumption rate of around 2.4 W/m² can be found with the mean radiant temperature of 24 °C, which is 2 °C lower than the room air temperature assumed for this calculation. There are usually some radiant heat sources such as glass windows absorbing more or less the incident solar radiation and electric-lighting fixtures mounted on the ceiling, computer screens and so on. Therefore, the mean radiant temperature is usually much higher than 24 °C, say 29 to 30 °C. There are some cases that it reaches even higher, almost 32 °C. If this is the case, the human-body exergy consumption rate becomes slightly larger, from 2.5 to 2.7 W/m².

The discussion above suggests that passive strategies for indoor thermal environment control such as solar control by external shading device over glass windows and natural ventilation should come to the first priority and then there need to be an active cooling system, which can well suit them, that is radiative cooling [Shukuya 2008]. The development of low-exergy cooling systems is to be made on this direction, which is consistent with that of low-exergy heating systems.

According to the previous studies with respect to human-body exergy balance in winter, there is a thermal environmental condition which brings about the lowest exergy consumption rate [Isawa et al. 2002; 2003, Prek, 2005]. It is again interesting that there is such a condition that brings about the lowest exergy consumption rate even in summer.

Figure 5: Relationships between human-body exergy consumption rate, whose unit is W/m²(body surface), and the combination of mean radiant temperature and air movement under a summer condition (33°C;60%rh). Room air temperature and relative humidity are assumed to be 26 °C; 50%rh for the indoor air condition by convective cooling.
5 Conclusion

A state-of-the-art development of the human-body exergy balance equation is described briefly and some numerical results were discussed. “Warm” radiant exergy plays an important role in winter condition, while on the other hand, “wet” exergy in addition to the reduction of warm exergy and the enhancement of cool radiant exergy does it essentially in summer conditions. There exists the lowest exergy-consumption rate of human-body for summer conditions as there exists such lowest rate for winter conditions. It suggests that the control of long-wavelength radiation is very important for summer to make it possible an effective use of natural ventilation.

The above discussion has confirmed that the development of “low-exergy systems” for heating and cooling are on the right track.

References


High Performance Indoor Environments with LowEx Demand

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## 1 Introduction

Heating, ventilation and cooling of buildings is responsible for 30-40 % of the energy consumption in buildings and a corresponding significant amount of CO₂ emission. The energy is used to provide acceptable indoor environments for people, which means healthy and comfortable indoor environments that also are optimal for the productivity of people. Since 2006 the European Energy Performance of Buildings Directive [EPBD 2002] has been implemented in building codes on a national level. For new and existing buildings this requires a calculation of the energy performance of the building including heating, ventilation, cooling and lighting systems, based on primary energy. Each building must have an energy certificate and regular inspections of heating, cooling and ventilation systems must be performed.

A new recast of the EPBD has just been published. This requires that by 2020 all new buildings will be near zero energy buildings. This has increased the focus on energy efficiency of buildings, systems and there components. It is however extremely important that the reduction in energy demand is made without reducing the indoor environmental quality.

## 2 High Performance Indoor Environment

A high performance indoor environment must take into account the following parameters:

- **Physical factors**
  - Thermal Comfort
  - Air quality (ventilation)
  - Noise-Acoustic
  - Illumination
- **Personal factors**
  - Activity
  - Clothing
  - Adaptation
  - Expectation
  - Exposure time
The European standard EN15251 (2007) includes recommended indoor environmental criteria for all the physical parameters. It may be debated if these criteria also will result in a high performance environment. One important factor is here individual control. People are very different regarding the requirements to the environment to be comfortable and perform optimal. Therefore a possible personal control is very important; but this is not dealt with in the standard. The following sections will deal with specifications of high performance indoor thermal environment and indoor air quality. Illumination is also important for the performance of people and is requiring energy. The issues are here to use as much daylight as possible without increasing cooling load and then in the future to use energy efficient light sources like LED bulbs. The acoustic or noise do also have a significant influence on peoples comfort and performance; but not a direct influence on the energy demand of a building. There is however in many cases an indirect effect. As example when you want to use natural ventilation for cooling by window openings. If the building is in a noisy environment people will not open windows.

2.1 Thermal comfort

For the design of buildings and dimensioning of HVAC systems the thermal comfort criteria (minimum room temperature in winter, maximum room temperature in summer) shall be used as input for heating load and cooling load calculations. This will guarantee that a minimum-maximum room temperature can be obtained under design outdoor conditions and design internal loads.

The recommended criteria in EN15251 are given for three categories. Using a higher class with stricter criteria will result in higher calculated design loads and can then result in larger systems and equipment. As an example, thermal design criteria for different types of space can be found in Table 1 as minimum room temperature in winter and maximum room temperature in summer for spaces with sedentary activity.

As the energy calculations may be performed on a seasonal, monthly or hourly basis (dynamic simulation), the indoor environment is specified accordingly. In dynamic simulation the energy consumption is calculated on an hourly basis. Recommended values for the acceptable range of the indoor temperature for heating and cooling are shown in table 1.

Table 1 Recommended temperature ranges for comfort according to EN15251

<table>
<thead>
<tr>
<th>Type of building/ space</th>
<th>Category</th>
<th>Operative Temperature for Energy Calculations °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Heating (winter season), ~ 1,0 clo</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cooling (summer season), ~ 0,5 clo</td>
</tr>
<tr>
<td>Offices and spaces with similar activity (single offices, open plan offices, conference rooms, auditorium, cafeteria, restaurants, class rooms, Sedentary activity ~1,2 met)</td>
<td>I</td>
<td>21,0 – 23,0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>23,5 - 25,5</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>20,0 – 24,0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>23,0 - 26,0</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>19,0 – 25,0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>22,0 - 27,0</td>
</tr>
</tbody>
</table>

2.2 Indoor air quality and ventilation

When discussing problems with the indoor environment the focus is often on the requirements for ventilation. Increasing demand for lower energy consumption of buildings has resulted in decreasing heat losses due to transmission and tighter buildings. This may often result in too low ventilation rates. This fact and the introduction of many new building materials may often lead to unacceptable indoor air quality and building damage like mould.
Instead of specifying directly requirements for indoor air quality, most standards, building codes and guidelines specify a required ventilation rate in order to indirectly provide an acceptable air quality.

Originally, most standards and guidelines for required ventilation rates were given as the required outdoor air supply rate per person. Laboratory and field studies have subsequently shown that people and their activity (smoking, activity level), building and furnishing (floor covering, paint, furniture, cleaning, electronic equipment, etc.) and ventilation systems (filters, humidifiers, ducts etc.) may also contribute to indoor pollution. Even the outside air may be a source of poor indoor air quality.

Both people and building-related sources of pollution are taken into account in newer standards for the required ventilation rates in buildings, which include ASHRAE 62.1 (2007), and EN15251 (2007). The standards include a prescriptive method, where the minimum ventilation rates can be found in a table listing values for different types of space.

2.2.1 Ventilation rates

Even if we today have standards and guidelines for estimating the required minimum ventilation rate, they are far from being complete. The goal is of course to be able to calculate the required ventilation rate as straightforwardly as in cooling load calculations. We need to know the requirements for acceptable indoor air quality based on health, comfort and performance and we need to know the emission rates from all the sources. Unfortunately, this is not as easy as in cooling load calculations, where room and outside temperature (°C), energy emission (watts), heat storage, solar radiation (watts) are all evaluated with similar units and all affect the same parameter of the human body (heat balance). For indoor air quality, we have thousand of substances that are emitted from people, furnishing, systems, from outside etc., each of which may affect one or more organs of the body.

There is general agreement that when specifying the minimum ventilation rate both the “pollutant” contributions from people (and their activity) and from the “building (furnishing, building materials, HVAC systems) must be taken into account. And as the emissions from both types of sources influence the odour level (as detected by the nose) we should add the contributions and the ventilation rates, just as when there are 5 occupants you must provide 5 times the ventilation rate for one person. The difference is that the perception of the occupants cannot be added linearly, so that when doubling the sources one should not expect the number of occupants dissatisfied to double. This is the case when comfort is the main criteria. If we consider health the emissions from different sources may influence different organs so if you ventilate for one substance you will also dilute another. In most cases the comfort requirements (odour) will lead to the highest minimum ventilation rate.

A minimum ventilation rate per person and a minimum ventilation rate per square metre floor area are required. The two ventilation rates are then added. The person-related ventilation rate should take care of pollution emitted from the person (odour and other bio effluents) and the ventilation rate based on the person's activity and the floor area should cover emissions from the building, furnishing, HVAC system, etc.

The design outdoor airflow required in the breathing zone of the occupied space or spaces in a zone, i.e., the breathing zone outdoor airflow (Vbz), is determined in accordance with the equation:

\[ V_{bz} = R_{p} P_{z} + R_{a} A_{z} \]  

(1)
Where:

- \( A_z \) = Zone floor area: the net occupied floor area of the zone \( m^2 \),
- \( P_z \) = Zone population: the greatest number of people expected to occupy the zone during typical usage.
- \( R_p \) = Outdoor airflow rate required per person: these values are based on adapted occupants in EN15251 and un-adapted in ASHRAE-62.1.
- \( R_a \) = Outdoor airflow rate required per unit area.

The rates are in EN15251 specified for three categories of indoor air quality, based on the prediction that a certain percentage of visitors will find the air quality unacceptable (see Table 2). The design levels are thus adequate for people who walk into a space. It is debatable if this should always be the case. People adapt very quickly to the odour (bio effluents) in a space while there is less adaption to emissions from building materials and tobacco smoke (odour and irritants, Gunnarson-1992). To provide an acceptable perceived air quality for occupants (who have adapted to the air quality for at least 15 min.) it is estimated that one third of the ventilation rate is sufficient i.e. for category II 2, 5 instead of 7 l/s per person. The ASHRAE Standard 62.1 for ventilation and indoor air quality defines ventilation levels for adapted persons (occupants).

In addition, the minimum recommended ventilation is increased with a building-related ventilation rate, in order to take into account the emissions from the building and its systems (see Table 2). There is, however no general agreement on whether the contribution from the building should be added in full. Several studies indicate this is the best approximation, but it may not be valid for all types of pollutants. Here it is the contribution to the odour and irritation (perceived air quality) which must be taken into account. So it can be argued they all influence one organ (the nose) and so should be added. When the health risk is considered a simple addition can only be made for the same chemical component. Therefore in some countries it is recommended that the minimum ventilation rate should be specified as a value between the minimum level for people (bio effluents) and the higher rate that takes account of both occupant and building emissions.

Table 2: Basic required ventilation rates for diluting emissions (bio effluents) from people and three types of buildings for different categories of indoor environmental quality.

<table>
<thead>
<tr>
<th>Category</th>
<th>Expected Percentage Dissatisfied</th>
<th>People component l/s person</th>
<th>Building component</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Very low polluting l/s m²</td>
</tr>
<tr>
<td>I</td>
<td>15</td>
<td>10</td>
<td>0,5</td>
</tr>
<tr>
<td>II</td>
<td>20</td>
<td>7</td>
<td>0,35</td>
</tr>
<tr>
<td>III</td>
<td>30</td>
<td>4</td>
<td>0,2</td>
</tr>
</tbody>
</table>

Criteria for the ventilation rate may also be expressed as total rates per \( m^2 \) floor area (l/s per \( m^2 \)) or per occupant (l/s per occupant). By expressing it as a people part and as a building part it becomes easier to calculate required ventilation rates for non-typical levels of occupancy.

One issue is the rate for the building component for different types of buildings. Three categories of buildings are included in Table 2. There is, however, a need to establish procedures and test methods for materials on the basis of which the type of building pollution level can be determined.
2.2.2 Ventilation effectiveness

The ventilation rates specified in the standards (Table 2) are the required rates at breathing level in the occupied zone. The required ventilation rate at the room supply diffusers are calculated as:

\[
V = \frac{V_{bz}}{e_v} \tag{2}
\]

Where:

\[V_{bz} = \text{breathing zone ventilation} \]

\[e_v = \frac{C_e - C_i}{C_i - C_i} \tag{3}\]

Where:

\[e_v = \text{Ventilation effectiveness} \]
\[C_e = \text{Pollutant concentration in extract air} \]
\[C_i = \text{Pollutant concentration in supply air} \]
\[C_i = \text{Pollutant concentration at breathing level} \]

The ventilation effectiveness depends on the air distribution efficiency and the type and position of the pollution source(s), so this value is not only a system characteristic. In most cases it is assumed that the pollutant emission is uniform, so the ventilation effectiveness is the same as the air distribution effectiveness. For a fully-mixed ventilation system the value is 1 and the ventilation rates in Table 2 can be used for the design of the supply registers.

3 LowEx technologies

In the future we must focus on technologies for heating, cooling and ventilation of buildings, which can provide an optimal indoor environment using low valued energy (low exergy systems) and/or renewable energy sources. Most importantly is however first to decrease the loads. The heating and cooling loads are decreased by optimising the building design in an integrated design concept. The ventilation load can be decreased by selection of building material and furnishing with low emitting products, heat recovery and use of controlled natural ventilation part of the year. The best control of the indoor environment is often obtained by separating the heating-cooling function from the ventilation function. These are some of the technologies, which will be discussed in this paper:

- Thermal comfort
  - Increase Efficiency of Heating- and Cooling systems
    - Low temperature heating-High temperature cooling
  - Drifting temperatures
    - Decrease of peak loads
- Indoor air quality
  - Pollution sources
  - Ventilation effectiveness
    - Personal ventilation
  - Air cleaning
Ventilation is always required and cannot directly be reduced. Instead heat recovery is used.

The challenge is to use energy efficient technologies, which can use low valued energy (i.e. low exergy systems), to provide acceptable indoor environmental conditions. The following sections describe some of existing and future technologies that full fill these requirements.

3.1 Low exergy heating and cooling of buildings

In Northern Europe a heating system is still needed even if the insulation of buildings will increase significantly. However, in middle Europe the increased insulation may result in a very low heat demand and a full heating system may not be needed. Also global warming will in the future impact the need for a heating system in many geographical areas. This may lead to alternative solutions for heating of buildings.

On the other hand peoples wish for more comfort, future higher outside temperatures, heat islands in big cities will increase the use of cooling systems. Furthermore we must increase the use of renewable energy sources. This requires systems, which can be used for heating at relative low temperature (air-water) and used for cooling at relative high system temperatures.

3.1.1 Low-temperature heating – high temperature cooling

With the reduction in the heating loads and by intelligent building design to avoid a high cooling load combined with the use of large surfaces for supplying and/or removing energy from a space, it is today possible to heat and cool buildings with systems using a very small delta T in relation to the required room temperature. In Europe it is mainly water-based radiant heating and cooling systems that are used (figure 1). One advantage compared with air systems is the more efficient means of transporting energy.

Figure 1: Examples of the positioning of pipes in floor, wall, ceiling and slab.

Even if surface heating and cooling systems often have a higher thermal mass than other heating/cooling systems, they have a high control performance. This is partly due to the small temperature difference between the room and the system (water, surface) and the resulting high
degree of self-control. Studies on controllability of floor heating/cooling [Olesen 2001] show that floor heating control the room temperature as good as radiators. To avoid condensation on a cooled surface, there is a need to include a limitation on water temperature, based on the space dew-point temperature. Design and dimensioning of these systems including calculation of heating and cooling capacity can be done according to the standards EN15377 (2007).

3.1.2 TABS (Thermo Active Building Systems)

A new trend, which started in the early nineties in Switzerland [Meierhans 1996], is to use the thermal storage capacity of the concrete slabs between each storey in multi-storey buildings (TABS~Thermo Active Building Systems). Pipes carrying water for heating and cooling are embedded in the centre of the concrete slab (Figure 1). By activating the building mass, you will not only get a direct heating-cooling effect, but you will also, due to the thermal mass, reduce the peak load and transfer some of the load outside the period of occupancy (figure 2). Because these systems for cooling operate at a water temperature close to room temperature, they increase the efficiency of heat pumps, ground heat exchangers and other systems using renewable energy sources.

The peak-shaving is the possibility to heat and cool the structures of the building during a period in which the occupants may be absent (during night time), reducing also the peak in the required power (Figure 2). In this way energy consumption may be reduced and lower night time electricity rate can be used. At the same time a reduction of the size of cooling system including chillier is possible.

The performance and dimensioning of TABS can be done by full dynamic building simulations with commercial programs including calculation models for embedded pipes [Olesen and Dossi 2004].

3.1.3 Temperature drifts

The midpoint of the comfort temperature range should be used as a target value but the indoor temperature may fluctuate or drift within the range due to the energy-saving features or control algorithm. Letting the temperature drift during the day increases the possible use of energy storage in the building structure, which leads to a lower peak load, so systems can be sized smaller.

Figure 2: Example of peak-shaving effect (X-axes: time; y-axes: cooling power W)
1) heat gain, 2) power needed for conditioning the ventilation air, 3) power needed on the water side, 4) peak of the required power reduction.
3.1.4 Exergy analysis

"Energy saving" and emission reduction are both affected by the energy efficiency of the built environment and the quality of the energy carrier in relation to the required quality of the energy. Taking into account qualitative aspects of energy leads to introduction of the eXergy concept in comparison of systems. Energy, which has a very limited convertibility potential, such as heat close to room air temperature, is low valued energy. Low eXergy heating and cooling systems use low valued energy, which is delivered by sustainable energy sources (e.g. by using heat pumps, solar collectors, either separate or linked to waste heat, energy storage etc.). Common energy carriers like fossil fuels deliver high valued energy. The reason for "energy saving" being in quotation marks in the first sentence, is that we actually are talking about saving eXergy, not energy!

Future buildings should be planned to use or to be suited to use sustainable energy sources for heating and cooling. One characteristic of these energy sources is that only a relatively moderate temperature level can be reached, if reasonably efficient systems are desired. The development of low temperature heating and high temperature cooling systems is a necessary prerequisite for the usage of alternative energy sources. The basis for the needed energy supply is to provide occupants with a comfortable, clean and healthy environment.

Figure 3 is showing an example of a calculated energy flow and exergy flow from primary energy, heat generator, emission in room and loss to the outside. The figures show that a low temperature heating system will result in less exergy consumption.

![Exergy and Energy Flow Diagram](image)

Figure 3: Examples of exergy and energy flow for three type of heating systems. (IEA-Annex 37).

3.2 Indoor air quality-Ventilation

One serious problem is how to ventilate if a building is located in an area with poor outside air quality or if there is a time of the day (e.g. rush hour) when the outside air quality is unacceptable. In some cases it might even be better to reduce ventilation under these circumstances, and the use of air cleaning technologies can be a better solution.

3.2.1 Source control

The most important “technology” to reduce ventilation rates is source control. One clear example of that is the regulation in most countries that you can not smoke indoors in public places. We have good knowledge about the required ventilation for the “people” component, while the “building” component is not very well documented. There is an urgent need for better certification and labeling of the materials used in buildings and we must also develop ventilation standards that favor the
manufacturers of “good” (low polluting) materials. A start has been made by defining three types of buildings in EN15251, but the method for evaluating to which type an existing or projected building should belong is not good enough.

3.2.2 Ventilation effectiveness

The ventilation effectiveness or air distribution efficiency is a function of the position and type of supply and return grills, and depends on the difference between supply and room temperature and on the total amount of airflow through the supply grill. The air distribution effectiveness can be calculated numerically or measured experimentally. Typical examples of ventilation effectiveness/air distribution effectiveness are shown in Figure 4 [CR1752 1996].

![Diagram of ventilation systems]

<table>
<thead>
<tr>
<th>Mixing ventilation</th>
<th>Mixing ventilation</th>
<th>Displacement ventilation</th>
<th>Personalized ventilation</th>
</tr>
</thead>
<tbody>
<tr>
<td>T supply - T supply</td>
<td>Vent. effect.</td>
<td>T supply - T supply</td>
<td>Vent. effect.</td>
</tr>
<tr>
<td>°C</td>
<td>°C</td>
<td>°C</td>
<td>°C</td>
</tr>
<tr>
<td>&lt; 0</td>
<td>0.9 - 1.0</td>
<td>&lt; -5</td>
<td>0.9</td>
</tr>
<tr>
<td>0 - 2</td>
<td>0.9</td>
<td>-5 - 0</td>
<td>0.9 - 1.0</td>
</tr>
<tr>
<td>2 - 5</td>
<td>0.8</td>
<td>&gt; 0</td>
<td>1</td>
</tr>
<tr>
<td>&gt; 5</td>
<td>0.4 - 0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T room</td>
<td>-</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4: Typical examples of ventilation/air distribution effectiveness.

The air distribution effectiveness takes into account the air distribution in a space, but does not take into account how effectively the outside air is transported through the ducts to the space. If the system has any air leakage, the amount of ventilation air must be increased. This is not dealt with in EN15251, but is mentioned in ASHRAE 62.1.

The rates given in the Tables are based on full mixing and in practice the ventilation effectiveness is very seldom taken into account. One complication is that some systems may have a different ventilation effectiveness summer and winter. If the supply temperature is lower than room temperature the ventilation effectiveness is normally 1 or higher, but if the ventilation system is used for heating in winter the ventilation effectiveness could be as low as 0.5, and the ventilation rates should really be doubled. More information and a greater emphasis on this factor are required.

The values in table 4 indicates that you should avoid to use warm air for heating and supplying the air directly to the occupants breathing zone (personal ventilation) is an efficient technology that can improve indoor air quality and reduce energy use by reducing the ventilation rates.

3.2.3 Air cleaning

Air cleaning is not taken into account at all in EN15251, while ASHRAE 62.1 by using the analytical procedure can allow some credits for air cleaning. There is an increased interest in the development of air cleaning equipment. This may be an acceptable way of reducing the amount of outside air, saving energy and still having an acceptable indoor air quality. However, better test methods for air cleaners are required, because at present the test is usually based on chemical measurements and the resulting effect on odour or perceived air quality is not taken into account. It is also very important to specify which kind of “pollutants” should be used when testing. Some air cleaners may work well on VOC’s (emission from materials) but have zero or even a negative effect if the source is people (bio effluents).
4 Conclusions

In the future it will be required to obtain high performance indoor environment in buildings with a minimum use of energy. It is a further requirement that the energy used must be of low quality (low exergy) and with a majority as renewable energy sources.

This requires first an integrated design to reduce the heating, cooling and ventilation loads by optimising the building design combined with the systems design.

For heating and cooling this requires systems that will use system temperatures for heating and cooling very close to the desired space temperatures. Large surface water based radiant heating and cooling systems will meet these requirements.

For ventilation the indoor pollution sources must be reduced by a good selection of low emitting materials. Then the required amount of ventilation must be delivered to the breathing zone in an efficient way and the systems must include heat recovery. For many workplaces a personalised ventilation systems will meet this requirement and besides give the occupants some personal control. To reduce the amount of ventilation and energy use further there is a potential in using air cleaning technology.

5 Literature


EN15377-1 (2007): *Design of embedded water based surface heating and cooling systems: Determination of the design heating and cooling capacity*.


Practical guidelines for LowEx Buildings

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1 Introduction

One of the goals of the final conference within Annex 49 “Low Exergy Systems for High-Performance Building and Communities” is to present concepts for the design of energy-efficient LowEx Buildings. LowEx buildings, as they are treated in this paper, can be heated by low-temperature energy sources and cooled by high-temperature sources. The energy supply in such buildings is based on the use of renewable energy sources (RES) and environmental energy, and efficient community energy-supply systems. In addition, LowEx buildings can be characterized by low heating and cooling loads, not exceeding 10 W per m² of living space. The guidelines are sets of rules, operating procedures and simplified calculation methods that enable the selection and optimization of LowEx systems for buildings. Four cases will be presented in this paper.

2 Case Studies

2.1 District heating with dispersed LowEx heat sources
[S. Medved, J. Vetršek, 2009]

EU guidelines and national requirements for the rational use of energy in buildings foresee an increased share of RES in the supply of energy. The minimum fraction of the heat supplied from RES is commonly expressed as a share of the final energy or as a percentage of the generated heat. For example, in Slovenia 25% of the generated nominal heat power was required (PURES 2008), and from 2011 on, at least 15% to 25% (depending on the RES) of the final energy consumption in a building should be provided from RES (PURES 2010). In the case of existing district heating systems, these requirements can be achieved by introducing dispersed sources of heat, such as solar heating and cooling systems, geothermal sources or heat pumps. The potential of such dispersed heat generation will be shown in the case of the renovation of a district heating system in the CONCERTO local community of Zagorje ob Savi. This study was made in the frame of the REMINING-LOWEX project. The district heating system supplies heat to buildings with a total area of 72,000 m². These buildings, with their 2400 inhabitants, were built between 1953 and 1990.
Figure 1: District heating system in the CONCERTO community of Zagorje ob Savi. The dots represent the 18 heat substations (HSS), where buildings with an aggregate living area of 72000 m² are supplied with district heat. The blue circles indicate substations with domestic hot-water heating. One-fifth of the inhabitants are provided with hot tap water via the district heating system.

The thermal response of the system was modelled using an adapted Trnsys numerical tool. This adaptation includes a newly developed Type 262 for the modelling of the heating substation with the dispersed heat-generation system. This type can be used for the modelling of the heat supply or the demand at each of the substations. Solar heating, a low-temperature geothermal source and HP can be selected as the dispersed heat generators, using the network of the district heating system for the heat storage. Altogether, the modelling of the buildings’ thermal response, the district heating system loop’s thermal response and the time-dependent heat delivery and demand in up to 18 substations can be simultaneously evaluated. In addition, the model was verified with data from the SCADA control system data.

The first stage of the research covers an analysis of the buildings’ energy-refurbishment measures. The aim was to determine the hour-by-hour heat demand and the decrease in the nominal heating power. This allows us to determine the potential for enlarging the district heating network without changing the (relatively new in this case) central heat generator. Two levels of energy refurbishment were predicted – the CONCERTO guidelines and the passive building standard. The thermal characteristics of the refurbished buildings are listed in Table 1.

Table 1: Thermal characteristics of the existing, CONCERTO and passive buildings

<table>
<thead>
<tr>
<th></th>
<th>$U_{\text{wall}}$ (W/m²K)</th>
<th>$U_{\text{roof}}$ (W/m²K)</th>
<th>$U_{\text{window}}$ (W/m²K)</th>
<th>ventilation</th>
</tr>
</thead>
<tbody>
<tr>
<td>current (on average)</td>
<td>1.20</td>
<td>2.80</td>
<td>1.8</td>
<td>natural</td>
</tr>
<tr>
<td>CONCERTO buildings</td>
<td>0.23</td>
<td>0.18</td>
<td>1.8 (Zagorje case study)</td>
<td>natural</td>
</tr>
<tr>
<td>passive buildings</td>
<td>0.15</td>
<td>0.10</td>
<td>0.7</td>
<td>mechanical; $\eta &gt;90%$</td>
</tr>
</tbody>
</table>

Fig. 2 shows the useful energy needed to heat the buildings and the domestic hot-water heating (for HSS 3, 4 and 5) connected to each of the substations for the current status and the two levels of the buildings’ energy refurbishment. The energy demand in the Zagorje district heating system could be decreased by 32% (-2.4 MWh/a) in the case of the CONCERTO standard refurbishment and up to 64% (-4.5 MWh/a) in the case of the passive-house standard refurbishment. As well as decreasing the energy demand, the refurbishment results in a decreased heating load, as shown in Fig. 3. District heating systems can also be enlarged and new consumers connected without replacing the boiler. In
the case of the analyzed district heating system, between 1.5 MW and 2.3 MW can be achieved with respect to the refurbishment standard.

Figure 2: Final heat demand of the buildings connected to the heat substations in the Zagorje district heating system with respect to the refurbishment standard and the cumulative yearly final energy demand. The dark-blue values represent the heat demand for domestic water heating.

Figure 3: Nominal heating load of the buildings connected to each of the substations in the district heating system with respect to the quality of the refurbishment. The cumulative heating load is presented in the right-hand column. The dark-blue values represent the heating load of the domestic water heating.

A decrease in the heat demand and the heating load has a consequence for the efficiency of dispersed RES heating sources. In order to determine this, the solar heating systems installed on buildings connected to the heat substations 3, 4 and 5 were analyzed. Areas of 120 m² (HSS 3), 600 m² (HSS4) and 600 m² (HSS5) were proposed with regard to the available roof area. Fig. 4 shows the solar fractions for the space and domestic hot-water heating in these buildings. A large increment in the solar fraction can be seen for the passive buildings. Additionally, the advantage of connecting a dispersed solar heating system to the district heating network can be seen in Fig. 5, because any surplus of heat can be transferred to the other consumers via the network. The importance of energy conservation is obvious, since a district network system can operate with lower temperatures in the case of passive buildings (in the case study $T_{\text{max}}$ was set at 70°C for the passive buildings’ heating and at 95°C in the other cases).
Guidelines

Rational energy use, especially in the development of low-energy communities, has a significant impact on the RES integration efficiency and the share of RES in the total energy supply. The impact of energy refurbishment on dispersed sources of renewable heat use can only be established if a coupled model, including the thermal response of the buildings and the thermal response of the district heating system, is used. This allows planners to modify and adapt the operating conditions of district heating systems to the dynamic response of the heat demand. Changes in the local meteorological conditions need to be taken into account when new facilities are being planned, since a reduced heating demand due to climate change is a common occurrence. When applying an extremely low-energy building standard (like with passive houses) the new design principles of RES integration need to be taken into account. This places more stress on the domestic hot-water supply; for example, the principle of heating-system temperature stratification that enables cascade operation should be used. In such a system a solar thermal system could have the role of a high-temperature heat generator. If and when the RES heat directive is implemented, dispersed RES heat sources connected to a district heating system could boost investments in RES technologies, since investors will not be limited to covering only their own needs.

2.2 LowEx ventilation and solar heating

[C. Arkar, S. Medved, 2008]

Decreasing the energy demand in a LowEx building can only be achieved with excellent thermal insulation, extreme airtightness and a high-efficiency mechanical ventilation system. Since a decentralized mechanical ventilation unit with heat recovery makes possible a lower electricity consumption and better adjustment to the users’ demands, such units have received much attention in recent years. Decentralised ventilation units can be integrated into thermally insulated facade elements, and they can be constructed in such a way as to enable solar heating. An example of such a device is shown in Fig. 5. The unit consists of two ventilated air gaps that are separated by a surface with an extended heat-transfer area. The exhausted air flows thought the inner cavity and the thermally activated insulation panel in such a way that the heat losses though the panes are almost negligible. Fresh air flows through the outer cavity with a solar-absorbing outer surface and it is preheated with solar energy and by the exhausted air.
Using the CDF simulation tool the temperature and velocity fields for sets of flow rates for fresh and discarded air were established for different temperature differences between the ambient and indoor temperatures (ΔT), the absorbed solar radiation (α_s G_{glob,lu}) and the IR emissivity (ε_{IR}) of the outer surface of the facade. The effectiveness of the heat recovery $\eta$ in the case of an air flow rate of 60 m$^3$/h per 1 m width of facade is shown in Figure 6. For a determination of the system’s performance, a multi-parametric numerical model was developed and verified with experiments.

**Figure 5:** A façade-integrated double-cavity decentralized ventilation unit with heat recovery and solar heating

**Figure 6:** Heat-recovery effectiveness as a function of the solar radiation and the IR emissivity of the façade surface for a ventilation air flow rate of 60 m$^3$/h per 1-m-wide element, where $T_{\text{outdoor}} = 0^\circ C$ and $T_{\text{indoor}} = 20^\circ C$ (left). Comparison of the CFD established and the modelled heat-recovery effectiveness.
Guidelines

Based on the results of the numerical simulations, a multi-parametric model for a determination of the effectiveness of the heat recovery $\eta$ for sets of air flow rates ($20 < V < 100$ m$^3$/h per 1 m wide), absorbed solar radiation ($0 < \alpha_s G_{\text{glob,}b} < 800$ W/m$^2$), temperature difference between the indoor and outdoor temperatures ($-20^\circ\text{C} < \Delta T = T_{\text{indoor}} - T_{\text{outdoor}} < 20^\circ\text{C}$) and the thermal emittance of the external surface ($0.1 < \varepsilon_{IR} < 0.9$) was designed for the device presented in Fig.5:

$$\eta = \prod_{i=1}^{3} f_i(\zeta_i) + (\alpha_s G_b) \prod_{i=1}^{3} g_i(\zeta_i) \quad \zeta_i = \{ \dot{V}, \Delta T, \varepsilon_{IR} \}$$

$$\eta = f_1(\dot{V}) f_2(\Delta T) f_3(\varepsilon_{IR}) + g_1(\dot{V}) g_2(\Delta T) g_3(\varepsilon_{IR}) (\alpha_s G_b)$$

where

$$f_1(\dot{V}) = 0.219 - 0.009 \cdot \ln(\dot{V})$$

$$f_2(\Delta T) = 0.656 \cdot (T_i - T_b)^{0.176}$$

$$f_3(\varepsilon_{IR}) = 3.017 \cdot \varepsilon_{IR}^{0.09}$$

$$g_1(\dot{V}) = 0.693 - 0.11 \cdot \ln(\dot{V})$$

$$g_2(\Delta T) = 0.1657 \cdot (T_i - T_b)^{0.993}$$

$$g_3(\varepsilon_{IR}) = 0.55 \cdot \varepsilon_{IR}^{0.14}$$

2.3 Weather-predicted operation of free-cooling system
[S. Medved, K. Dovrtel, 2010]

Because of the low cooling loads, free cooling by ventilation offers an efficient way of providing thermal comfort and decreasing the peak electricity load in LowEx buildings. However, additional thermal storage is often required for efficient free cooling in order to compensate for any periodic ambient temperature variation. Thermal storage can be realized, for example, by using a concrete wall/floor with an air-duct heat exchanger or as an additional thermal storage unit combined with an existing building HVAC system.

Figure 7: Examples of heat storage in a free-cooling system – heavy building construction with ducts (left), PCM heat-storage package installed in a HVAC system (right) [xia - Intelligent architecture 04-06/10]

In the current practice of building service system control, the system operation depends solely on the instantaneous parameters of the outdoor and indoor environments. Since the night-time free cooling has to be adapted to the amount of cold needed during the hot period of the next day, the operation of
the system should be based on a predicted future environmental temperature and the temperature response of the building. In order to implement so-called “predictive controlling”, several steps should be taken: gathering the relevant weather-forecast information data, selecting the system and defining the system model, determining the building’s thermal response, selecting the optimization criteria and selecting the optimal operation of the system. The importance of predictive controlling will be shown in the case of a free-cooling system with heat storage, which is presented in Fig. 8. The system consists of heat storage, air ducts and a fan with variable flow control. During the night (solid line) the system intakes the ambient air and divides it into two streams – one for cooling the building and other for cooling the heat storage. During daytime operation the ventilation air is pre-cooled in the heat storage and flows into the building (dashed line). Since the ventilation system has a limited capacity, the maximum cooling potential is limited as well. Therefore, the ratio between the air flow rate through the heat storage and the air flow rate into the building during the night has to be optimized to ensure the optimization criteria. This could be the maximum inlet temperature of the fresh air, the maximum decrease of the peak cooling power or other requirement criteria. This can be accomplished by using weather-forecast data and the optimization computer tool. Such a tool was developed using the Mathematica software package with the Interior Point function extreme solution method. In the presented case the criteria function was the maximum amount of cold supplied to the building over the next 24 hours.

An example of a building size of 150 m² with a volume of 320 m³ was analyzed as a case study. To achieve sufficient ventilation, an air-exchange rate per hour of at least 0.5 should be supplied. The minimum air supply is thus \( m_{\text{min}} = 160 \text{ kg/h} \). The maximum air flow rate supplied by the system is limited to \( m_{\text{max}} = 5m_{\text{min}} \). The indoor air temperature in the building was set to be a constant 24°C. The optimization process is divided into two steps – first, the maximum temperature of the heat storage \( T_{\text{sh}} \) at the start of the daytime operation phase is calculated to satisfy two conditions for the system’s daytime operation: a constant minimum fresh air flow rate (0.5 h⁻¹ in our case) and a maximum inlet air temperature (in our case equal to the chosen indoor temperature of 24°C). In the next optimization step – the previous night-time operation phase – the optimal time-dependant ratio between the air flow rate into the building and the air flow rate into the heat storage is calculated in such a way that the temperature in the heat storage at the end of the night-time period does not exceed the maximum temperature established during the first optimization step. In this case the maximum amount of cold is supplied to the building during the night-time. In Fig. 9 the air temperatures, the heat-storage temperature and the air flow rates into the building and into the heat store are shown for three different operating modes, which all satisfied the optimization conditions.
Figure 9: Ambient air, ventilation air, heat-storage temperatures and air flow rates during a period of 24 h for the same free-cooling system operating with three different modes – the “extremely good” mode (the system provides the maximum amount of cold with a variable flow rate), the operation mode in which the system provides the maximum amount of cold at a constant flow rate, and the “extremely bad” mode (the system provides the minimum amount of cold). In the illustrated case the flow rate was optimized during night-time operation for 5 time intervals.

The total amount of cold supply into the building is 1.6% greater if the system operates with a variable flow rate compared to the constant flow rate mode, and it is 30.8% greater if the system operates in the “extremely bad” mode. In the case of a greater daily environmental air-temperature amplitude (in the illustrated case it was chosen to be 6 K) the difference would be even more evident.

Guidelines

The energy sources for all the systems that utilize natural sources of energy, including the free cooling in the presented case study, share a common flaw – the energy source is only available at certain times of the day/year, is limited in its magnitude and is not arbitrarily available. The prediction of the natural energy sources’ potential and the resulting response of the buildings’ service systems are therefore mandatory for achieving efficient operation. The results from the presented case showed the need for a “predicted controlling” of LowEx systems.

2.4 LowEx building-façade element

Prefabricated, large panel, building-façade elements are widely used. Such composite elements consist of two steel facings and an insulation filling, which in most cases is made of mineral wool. Although steel facings are impermeable to water and water vapour, there are several reasons why moisture can appear inside such elements. The reason could be cracks and flaws in the steel facings, loose joints between the façade panels or the inappropriate storage of the panels. Fibrous thermal insulation has a high thermal resistance and a low diffusion resistance to water vapour. Because of this low diffusion resistance and the temperature dependence of the water-vapour pressure, the water vapour can easily diffuse from the boundary that has a higher temperature than the boundary with the lower temperature. During this process the water-vapour molecules evenly fill the whole volume of the fibrous thermal insulation, which makes the process of heat and mass transfer one dimensional. Because the evaporation/condensation process occurs continuously inside the thermal insulation, the mass flow of water-vapour molecules is accompanied by a considerable amount of enthalpy flow, which can exceed the sensible heat flux by several times. Such an enhanced heat transfer lasts until all the water vapour condenses on the cold boundary. The process of mass transfer finishes at that point and the heat flux reduces to the level of the dry façade element (Fig. 10).
Figure 10: Temperature distribution and heat flux through a composite, water-tight, building-facade element if the element contains liquid water: a - liquid water is placed at the boundary with a higher temperature, the heat is transferred by conduction only and the heat flux is equal to that in the dry element; b – the heat flow is the sum of the heat conduction and the latent heat flow; the process of continuous water evaporation and condensation starts; the heat transfer is enhanced by water-vapour latent heat flux; c – the condensation ends at the cold boundary; heat is once again transferred by conduction only.

If it was possible to change the diffusion resistance of the thermal insulation material or the physical properties of the liquid, this could be used for a controlled enhancement of the heat transfer through the facade element towards the building’s interior during sunny winter days, when the temperature of the outer boundary is higher than the interior temperature, or towards the surroundings during cool summer nights, when the temperature of the outer boundary is lower than the interior temperature. Such an element will act as a LowEx application for the free cooling and heating of buildings.

Figure 11: Time-dependant heat flow rate through a 100-mm-thick composite facade element as a result of the steep change of the cold boundary temperature from 20°C to 5°C. The sample consists of 254 g of water per m² of sample surface area.

The main goal of our research was to find the relationship between the daily amplitude of the outdoor boundary temperature and the mass of water necessary to provide the maximum heat-transfer rate and to ensure that the period of the process is within 24 hours.

An example of enhanced heat transfer in a 100-mm-thick composite facade element is shown in figure 12. for a wet (a) and a dry (b) sample. The average daily temperature on both boundaries was equal to 20 °C, while the outer boundary daily temperature amplitudes were selected as \( T_a = 5 \text{ K}, 10 \text{ K}, 15 \text{ K}, 18\text{K} \). In the case of the wet sample the mass of water was adjusted in such a way that the heat flux within a 24-hour period was a maximum. The facade element consisted of 38 g/m² of water when \( T_a \) was 5 K, 68 g/m² of water (\( T_a=10\text{K} \)), 93 g/m² (\( T_a=15\text{K} \)) and 108 g/m² (\( T_a=18\text{K} \)).
Figure 12: Heat-flow development through the wet (a) and the dry (b) composite building facade element.

### Guidelines

As yet unavailable research will be focused on the effect of a membrane with various vapour resistances that is integrated inside the insulation slab in such a way that an enhanced heat-transfer process can be controlled. In this way such elements will become a LowEx application for the free cooling and heating of buildings.

### 3 Conclusion

The rapid progress of RUE in buildings enables the more widespread use of high-performance energy systems, like low-exergy free heating and free cooling or solar heating and cooling. To realize the great potential of LowEx systems, innovative principles of integration into the buildings’ structures, multivalent system functioning and, since natural energy sources are limited in duration and power, improved methods of control, must be developed further. This article has presented some of the possibilities.

### 4 Literature

[S. Medved, J. Vetršek, 2010] S. Medved, J. Vetršek, 2010; District heating systems optimization with integration of distributed heat generation from renewable sources and demand side measures; Report of Remining LowEx project; Faculty of Mechanical Engineering, University of Ljubljana.


The LowEx Approach
for Real Live Building Projects

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Until the year 1870, man had only utilized the simple combustion process to generate heat for cooling and heating. The introduction of the 2nd Law of thermodynamics was a turning point of the history of civilisation. It was possible to produce mechanical power out of heat. Unfortunately only the engine running a Carnot power cycle was used to turn heat flow into power. The reverse, or refrigeration cycle, in which heat pumps move heat using power as an input was not used for heating. Even today, most heating systems still rely on the combustion process. After World War II air conditioning for warm climates became common. In this case heat pump served a heat removal function for cooling down rooms. Unfortunately, the generation of the electricity to operate the heat pumps is produces with inefficient fossil fuel combustion processes, increasing the primary energy demand relative to onsite combustion for heating.

The result of the use of these combustion-dependant technologies can be seen in the curve of the CO2-concentration n the atmosphere.

Only in 1956 was exergy introduced as an expression, and it wasn’t until the year 1995 that the Federal office for energy in Switzerland correctly implemented for a district in Geneva the word exergy rather than energy for power distribution. Very few people were aware of the 2nd Law of thermodynamics.

In the year 2000, only about 20-30 people worldwide used exergy in the building sector. The task IEA Annex 37 and Annex 49 increased the attention towards exergy analysis to an enormous extent within only 10 years. The theoretical modelling of technical systems with the exergetic approach was very successful.

In our group at ETH in Zurich we decided 5 years ago to focus on the transfer of the new theory of low exergy building systems into practical work. We outlined two research streams, one on technical components and one on architectural planning and building modelling.

The first stream on new technical compounds creates a new type of building service systems. My assistants Luca Baldini, Forrest Meggers, Matthias Mast, Volker Ritter and Marcel Bruelisauer presented the results of their investigations different times within the Annex 49 group [1-9]. This work includes collaboration with Prof. Dr. Beat Wellig from the Lucerne University of Applied Science and Arts in Horw to develop low temperature-lift heat pumps along with a variety of technologies that can exploit this low temperature-lift [10,11]. We are on a very good track in this part of our work, because the Swiss industry is very interested in collaboration in this field. I shall outline two highlights:

1. The new low-temperature-lift turbo heat pump:
   Using a common piston compressor and 51340 as a refrigerant the measured COP were good at temperature lifts of 24 – 30°C and quite poor for temperature lifts below 15°C. We wanted to create a system optimised for the low temperatures possible in a low exergy system as illustrated in Figure 1.
Figure 1: Plot showing the change in COP of a heat pump with decreasing temperature-lift. Our goal is to create systems that can achieve temperature lifts of 15°C combined with a heat pump that operates with high g-value (the ratio of actual COP to the maximum ideal COP).

The results showed the importance of new research on very low temperature lift heat pumps. In collaboration with two other research groups, we are developing a new turbo-compressor heat pump using butane as a refrigerant. The oil-free machine will run on a speed of 300’000 rev. per minute.

2. The new hybrid photovoltaic solar panel:
Our group developed a new hybrid photovoltaic panel to produce a heat flow of 450 W/m² at a temperature of 10°C above ambient temperature at full insolation of 8000 W/m². The secondary effect of actively cooling the PV-Panel to 35°C increases the electrical output by 10-12%, or 140 Watt-el/m² instead of 125 Watt-el/m². The additional system to collect heat at the rear side of the PV-panel is very simple, as shown in Figure 2, because it does not aim for high temperature extraction. Therefore it is inexpensive to implement.

Figure 2: Picture of the backside of the hybrid photovoltaic solar panel. This inexpensive heat exchanger can capture 450 Watt/m² of heat at 10°C above the ambient outside temperature (appropriate for low exergy systems), while at the same time actively cooling the panel and increasing its electrical efficiency.
The combination of the PVT with the new heat pump leads to a higher efficiency compared to a normal thermal system. Imagine the potential of a system capturing high enough temperature heat to allow for a heat pump operation, as shown on Figure 1, with a COP of 10. By using the electrical efficiency of the hybrid solar panel of 10-12%, in essence the effectiveness of the heat supply would be more than 100% of the solar input. Clearly this is not possible with any solar thermal system.

In our second research stream, we try to bring low exergy theory to the planning-process in architecture. Since the number of parameters in active LowEx systems is much higher than in passive systems (such as Passivhaus), the problem of the high complexity makes it difficult for architects to use exegetic optimization tools. In order to overcome this problem a software module called DPV (Design Performance Viewer) has been developed in our group [12]. The geometric parameters of a Building Information Model (BIM) are imported into the DPV, where the energetic and exergetic calculations are made. The energy flow diagram and the chain of exergy usage are graphically displayed and can be interactively changed through changes in the 3D model. We are able to calculate the energetic and exergetic performance of a 3D modelled building within a few seconds. Recently, the dynamic calculation engine of Energy Plus has been implemented successfully to allow access to more dynamic annual calculations of annual performance calculations that were previously based on German EnEV standards or Swiss SIA standard.

In order to visualize the results of different solutions, 3 standardized figures (Sankey diagram, Spider graph, and NSE diagram) have been implanted as shown in Figures 3 and 4.

Figure 3: Sankey Diagram displaying the flows of energy in the building system. The arrows are color coded for different sources and the graphic changes interactively with changes in the 3D building design.
Conference “The Future for Sustainable Built Environments with High Performance Energy Systems”

Figure 4: The Spider graph in the background the NSE diagram in the foreground. The Spider graphic shows the breakdown of various energy uses between sectors. The NSE diagram plots the position of total annual exergy demand in kWh/m² on the x-axis and the CO₂ intensity of the exergy supply in kg/kWh, which allows independent improvements in efficiency and renewable supply.

These 3 diagrams show very quickly the performance of a solution. In spring 2010 we introduced the ZERO-Emission-lowEx idea. Zero Emission means, that neither CO₂ nor radioactivity should be emitted in the whole energy supply chain. The state of a building has to be under the 1kg CO₂/m².

Figure 5: NSE diagram depicting the constant CO₂ per year and area building lines with the goal being to reach under 1kg CO₂ per year and per m² building.
Now that we have set a goal for the CO\textsubscript{2} emissions, the y-axis becomes free in our NSE diagram for another parameter. We suggest the investment costs per m\textsuperscript{2} building area. This is shown in Figure 6.

![Figure 6: Plot of the specific exergy-demand and the specific costs.](image)

At the x-values of the specific exergy-demand versus the specific costs for the local investment are plotted, divided up into the base structure, the additional investments for insulation of the envelope, the costs for the technical systems, and on top of all the Zero Emission Supply-Investments (ZESI, i.e. investment in renewable supply) that have to be spent to produce the zero emission net delivered energy (the exergy).

We will integrate these cost calculations into the DPV within the next 2 years. Having this we can economically optimize the design of zero emission buildings. The exergy specific consumption is one of the most important parameters in the process.

Using these tools along with the array of technical systems that we have developed, we have implemented the LowEx concept into several building projects. I will present two projects that are detailed on the website, www.viagialla.ch. One is a renovation of the existing office building that houses our offices on the Science City campus of the ETH Zurich, and the other is a new construction of a multifamily house in Zurich. Both utilize the design process described above. The new construction will be the first installation of the new hybrid PV technology along with a heat pump connected to a dual-zone borehole that allows warmer temperatures from >300m depth to be utilized independently from cooler temperatures at <100m depth, helping to minimize the temperature lift. With our research we will prove the potential of a LowEx approach within real building installations.
References


BUILDINGS
Strategies for Integrative Building Design

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1 Introduction

The building sector is identified as providing the largest potential for CO2 reduction by 2020 and many countries across the world have set very ambitious targets for energy efficiency improvements in buildings. To successfully achieve these targets it is necessary to identify and develop innovative building and energy technologies and solutions for the medium and long term which facilitates considerable energy savings and the implementation and integration of renewable energy devices within the built environment.

Environmental design and control of buildings can be divided into two very different approaches. In the usual “exclusive” approach energy efficient building concepts are created by excluding the indoor environment from the outdoor environment through a very well insulated and air tight building construction. Acceptable indoor environmental conditions are established by automatic control of efficient mechanical systems. Next to this, there is a growing interest for developing buildings that cooperate with nature and make use of the available environmental conditions. In this “selective” approach energy efficient building concepts are created by using the building form and envelope as an intermediate between the outdoor and the indoor environment. Acceptable indoor environmental conditions are established by user control of the building envelope and the mechanical systems. It is important that the building is responsive to the fluctuations in the outdoor environment and the changing needs of the occupants, which means that the building should have the ability to dynamically adjust its physical properties and energetic performance. This ability could pertain to energy capture (as in window systems), energy transport (as air movement in cavities), and energy storage (as in building materials with high thermal storage capacity).

In a responsive building an optimum must be found between the, sometimes contradictory requirements from energy use, health and comfort. From the viewpoint of human coexistence with nature the approach is to make buildings “open” to the environment and to avoid barriers between indoors and outdoors, where from the viewpoint of energy savings the approach, for certain periods, is to exclude the buildings from the environment. The area between indoors and outdoors herewith becomes a more or less hybrid zone where the energy gains are not only rejected, but are stored, tempered, admitted or redirected, depending on the desired indoor conditions. Nowadays we are able to measure and control the performance of buildings, building services and energy systems with an advanced building management system (BMS). This opens a new world of opportunities. Buildings no longer act as ridged objects that need a large heating installation in winter and big cooling equipment during summer to “correct” the indoor climate, but buildings become an additional “living” skin around occupants, keeping them in contact with nature, but at the same time protecting them when necessary.

However, this design approach requires that building design completely changes from design of individual systems to integrated design of responsive building concepts, which should allow for optimal
use of natural energy strategies (day lighting, natural ventilation, passive cooling, etc.) as well as integration of renewable energy devices. Design teams including both architects and engineers must be formed and the building design developed in an iterative process from the conceptual design ideas to the final detailed design. However, a number of barriers appear when the borderline between architecture and engineering is crossed; the design process contains a lot of challenges to those who participate in the process.

2 The Integrated Design Philosophy

2.1 From component to concept

Efforts to minimize the building energy efficiency over the last decades have focused on efficiency improvements of specific building elements and building services equipment (component level). Significant improvement has been made. However the performance of individual elements is often heavily depending on the performance of the system they are part of. I.e. the performance of a heat pump depends on the performance of whole heating and cooling system which consists of a source, a distribution and a delivery part. The performance of a well insulated window no longer only depends on the insulation level of the glazing, but also on the window frame, the spacers etc. Innovations are shifting from component level to system level.

But also the system level approach is no longer appropriate. Buildings have become integrated concepts in which advanced systems work together to reach an optimal performance in terms of energy, comfort and health. And particularly on the overlapping field of building technology and building services, the responsive building elements, lies a great future potential to achieve the next steps in energy savings.

![Figure 1: Increasing energy demands](image)

With the integration of responsive building elements and building services, building design completely changes from design of individual systems to a design of integrated building concepts.

2.2 The responsive building concepts

Responsive building concepts in this paper are design solutions in which an optimal environmental performance is realized in terms of energy performance, resource consumption, ecological loadings and indoor environmental quality. It follows that building concepts are design solutions that maintain an appropriate balance between optimum interior conditions and environmental performance by reacting in a controlled and holistic manner to changes in external or internal conditions and to occupant intervention and that develop from an integrated multidisciplinary design process.
An integrated building concept includes all aspects of building construction (architecture, facades, structure, function, fire, acoustics, materials, energy use, indoor environmental quality, etc). It can be defined to consist of three parts:

- an architectural building concept,
- a structural building concept and
- an energy and environmental building concept

This corresponds to the professions involved in the building design and each concept is developed in parallel by the three professions using their own set of methods and tools - but in an integrated design process leading to an integrated solution.

### 2.3 The integrated design process

A responsive building concept can only be developed by an integrated design approach. Design teams, including both architects and engineers, are formed and the building design is developed in an iterative process from the conceptual design ideas to the final detailed design. Building energy use and HVAC equipment size are reduced without the use of sophisticated technologies, but only through an effective integration of the architectural and HVAC designs. The integrated design approach achieves this improved energy utilization due to the relationship that exists between the building, its architecture and the HVAC equipment. Besides this the integrated design approach also achieves an improvement in the environmental performance of the building, as well as fewer construction problems and lower costs.

In a sequential design process the engineer at the later stages of design more or less act in a reactive way, thus correcting the architectural design. The risk that poor design concepts are developed are therefore higher. There are a number of serious consequences if the proper decisions are not made at the conceptual design stage. The building will almost certainly cost more to build and operate (e.g. it often takes huge air conditioning equipment and much energy to compensate for poor orientation, window placement etc.). The cost is not only in terms of money, but also in the depletion of non-renewable resources, in the degradation of the environment and often also in poorer building performance in terms of comfort.

An integrated design process ensures that the knowledge and experience gained by an analytical consideration of design is formalized, structured and incorporated into the design practice. In the
integrated design process the expertise of the engineers is available from the very beginning at the preliminary design stage and the optimization of the architectural and HVAC designs can start at the same time as the first conceptual design ideas are developed. The result is that participants contribute their ideas and their technical knowledge very early and collectively. The concepts of energy and building equipment will not be designed complementary to the architectural design but as an integral part of the building.

2.4 Implementation barriers

A number of barriers appear when the borderline between architecture and engineering is crossed. Architects belong to the humanistic arts tradition while the engineer belongs to a technical natural science tradition. This often creates problems for architects and engineers working as a team, as the communication between the two groups rely on a common language and in this case the languages are at the outset very different.

The integrated design process is a holistic method that intertwines knowledge elements from engineering with the design process of architecture to form a new comprehensive strategy to optimize building performance. This implies evaluation and weighting of very different building performance characteristics that often are non-comparable, which requires willingness from all participants to reach acceptable compromises. The goal of integrated design is an improved and optimized building performance for the benefit of the building owner and the occupants. Changes in design process and methods will require investment in education and will always be more expensive for the designers in the beginning. Therefore it cannot be expected that architects and engineering consultants will be the main drivers for these changes unless the building owners and clients recognize the benefits and are willing to contribute to the investments needed to implement the changes.

3 Design Strategy

3.1 Boundary conditions

As in the classical design approach a sustainable design should start with a thorough analysis of the environmental conditions and determine the beneficial environmental design conditions as location of the building, sheltering, optimal orientation, solar and wind optimization and protection, ground coupling possibilities etc. This mostly takes place in relation to the architectural and esthetical design considerations, but is the first step in achieving an more energy saving design.

Next to it, comfort requirements and IAQ need to be considered. Fixed and uniform conditions as stated in the last decades can be transformed in adaptive conditions, related to the place, function, time and activity in the building. Also the considerations regarding local climates can lead to large energy saving potential.

3.2 Technical Solutions

In order to reach an integrated technical design solution and to develop an Energy and Environmental Building Concept it is necessary to define and apply a certain design strategy. In the IEA ECBCS Annex 44 project the design strategy is based on the method of the Trias Energetica method described by Lysen (1996). This Trias Energetica approach has been extended within the Annex 44 work with technologies that will be applied, depending on the design step.
Integrative Building Design

Figure 3: Illustration of IEA ECBCS Annex 44 Design Strategy and corresponding technologies

The left side of the pyramid shows the design strategy, and the right side of the pyramid shows the technical solutions in each of the steps. The figure clearly positions the responsive building elements as a technology that falls in the first step “reduction of energy demands” as well as in the second step “application of renewable energy sources”. An integrated design strategy, starts at the bottom of the pyramid and applies the strategies and technologies as follows:

**Step 1. Reduce energy demand.** Optimize building form and zoning, apply well insulated and air tight conventional envelope constructions, apply efficient heat recovery of ventilation air during heating season, apply energy efficient electric lighting and equipment, ensure low pressure drops in ventilation air paths, etc. Apply Responsive Building Elements if appropriate including advanced façades with optimum window orientation, exploitation of daylight, proper use of thermal mass, redistribution of heat within the building, dynamic insulation, etc.

**Step 2. Apply renewable energy sources.** Provide optimal use of passive solar heating, day lighting, natural ventilation, night cooling, earth coupling. Apply solar collectors, solar cells, geothermal energy, ground water storage, biomass, etc. Optimize the use of renewable energy by application of low exergy systems.

**Step 3. Efficient use of fossil fuels.** If any auxiliary energy is needed, use the least polluting fossil fuels in an efficient way, e.g. heat pumps, high-efficient gas fired boilers, gas fired CHP-units, etc. Provide intelligent control of system including demand control of heating, ventilation, lighting and equipment. The main benefit of the method is that it stresses the importance of reducing the energy load before adding systems for energy supply. This promotes robust solutions with the lowest possible environmental loadings.

### 3.3 Application of the design strategy

A roadmap for application of the design strategy in the various design stages is given in table 1. The heating cooling, lighting and ventilation design of buildings always involves all steps, when it is consciously recognized as in an integrated design process that each of these steps is an integral part of the heating, cooling, lighting and ventilation design, better buildings result.

**Step 1: Basic design focusing on reduction of energy demands.** In the first state of the design the focus primarily is on the reduction of demands for heating, cooling, lighting and ventilation by means of reducing internal heat loads and optimization of daylighting and reducing the heating, cooling and ventilation energy.
Priority in this is the reduction of internal and external heat loads. The internal heat loads can be reduced by the use of energy saving equipment as computers, copiers etc and by installing energy saving electric lighting. Most effective in this is the maximizing the daylight autonomy of rooms and thus reducing the energy use for electric lighting. As the efficacy of daylight is much higher that artificial light this counts both for reduction of electric energy consumption for lighting as for reducing the energy consumption for cooling.

The next step is to find an optimum in reducing the heating and cooling gains by an optimal surface to volume ratio, zoning, shading, insulation level and a demand controlled ventilation level. A special effort is required when applying long term heat storage. In that case heating and cooling gains over a year need to be tuned to each other to avoid long term imbalance. Decisions at the first step determine the size of the heating, cooling and lighting loads and good fabric design is essential for minimizing the need for services. Poor decisions at this point can easily double or triple the size of the mechanical equipment needed. Where appropriate, designs should avoid simply excluding the environment, but should respond to factors like weather and occupancy and make good use of natural light, ventilation, solar gains and shading, when they are beneficial.

At an early stage, it should be possible to modify the design to reduce the capacity, size and complexity of the building services, which can reduce the capital cost of the services without having to remove features from the design.
Table 4-1: Typical design considerations at each design phase

<table>
<thead>
<tr>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
<th>Step 4</th>
<th>Step 5</th>
<th>Step 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Design</td>
<td>Passive Heating</td>
<td>Basic Design</td>
<td>Design of Low Exergy Mechanical Systems</td>
<td>Heating System</td>
<td>Intelligent Control</td>
</tr>
<tr>
<td>Conservation</td>
<td>Heat Avoidance</td>
<td>Climatic Design</td>
<td>Application of Responsive Building Elements</td>
<td>Artificial Lighting</td>
<td>Advanced sensor techniques, model based and adaptable control algorithms, user interface, …</td>
</tr>
<tr>
<td>Heating</td>
<td>Cooling</td>
<td>Daylight</td>
<td>Responsive Lighting Systems</td>
<td>Mechanical Ventilation</td>
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<tr>
<td>Cooling</td>
<td>Lighting</td>
<td>Ventilation</td>
<td>Hybrid Ventilation</td>
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<tr>
<td>Lighting</td>
<td>Ventilation</td>
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Step 2: Climatic design though optimization of passive technologies. The second step involves optimization of natural and “free” gains from sun, wind and thermal storage through application of direct solar gains, free cooling, thermal mass application and natural ventilation. Effective functioning of these measures directly relates to the outdoor climate as available wind and sun conditions, day-night rhythm and earth temperature. Proper decisions at this point can greatly reduce the loads as they were created during the first step leading to the wanted reduction in size and complexity of the building services.
Step 3: Integrated system design and application of responsive building elements. Step 3 contains the design of integrated systems with responsive building elements. In this step the activation of building elements by building services enhances the further employment of building components. Energy gains in building elements are actively controlled by changing and influencing the physical behaviour and properties of the building components.

Step 4: Design of low exergy mechanical systems. To realise the comfort conditions required, mechanical systems for heating, cooling, lighting and ventilation are applied to handle the loads that remain from the combined effect of the previous steps. To enhance the application of renewable energy sources priority lies with low exergy mechanical systems. This counts for the energy generation part, the energy distribution part and the energy delivery part of the mechanical systems. Hereby a tuning of generation, distribution and delivery is crucial to reach an efficient and optimal performance.

Step 5: Efficient design of conventional mechanical systems. Step five consists of designing the (conventional) building services. Herewith it is important to ensure that the services operate in harmony without detrimental interaction or conflict. Many energy problems can be traced to a conflict between building services and many conflicts between services are control issues. An energy efficient design strategy should avoid this and the underlying reasons for conflict should be identified and eliminated to prevent carrying a flawed design forward. It is not a good policy to hope that the control system will resolve the conflicts.

Step 6: Design of intelligent control for optimized operation. Definitely more than in the past the intelligent control of the energy transport is crucial to come to a proper and efficient operation of the building, building services and renewable energy systems to reach an optimal energy efficiency. The systems therefore needs to be fed with the design considerations and must be able to tune to the different external and internal climate conditions and the comfort requirements of the building occupants. Advanced sensor techniques together with sophisticated control algorithms are still under development and need further improvement which is also the case for interfaces for user control and user/system interaction.

4 The IEA ECBCS Annex 44 Integrated Design Process

4.1 The iterative process

The Annex 44 integrated design process (IDP), creates a synergy of competencies and skills throughout the process by the inter-disciplinary work between architects, engineers, and others right from the beginning of the process. It ensures that different knowledge of specialists is introduced at an early project phase and takes into account a wide variety of opportunities and options from the very outset. It involves modern simulation tools, and leads to a high level of systems integration. It enables the designer to control the many parameters that must be considered and integrated, when creating more holistic sustainable buildings. The building design is developed in an iterative process from the conceptual design ideas to the final detailed design.
It is important to consider the whole process, structuring it into clearly defined sequences to improve the overview of goals, activities, actors and products and to switch between them. The intermediate workflows in each rough phase can be characterized by iteration loops.

The loops provide problem-oriented analyses of design alternatives and optimization based on the design strategy presented in Figure 6 a t/m c (split up figures from figure 4), and taking into consideration input from other specialists, influences from context and society that provide possibilities and/or limitations to design solutions as well as evaluates the solutions according to the design goals and criteria.

The actual design process is made up of a number of roughly-defined phases which demand for individual iterations within the phases and accompanied by a continuous review of project goals, objectives and criteria which serve as a “roadmap” throughout the entire design process.

4.2 Main design phases

The Annex 44 integrated design process includes the following main phases:

**Phase 1: Where to built and what to built:** It is essential to understand the climate characteristics of the building site for responsive building design. The climate data is useful not only for estimating heating- and cooling load of the building but also for creating passive design concepts. Analysis of site potential including wind, sun and landscape, urban development plans, analysis of clients’ profile and chart of functions create a roadmap of energy system principles, renewable energy systems, indoor...
environment and construction solutions. The outcome is an analysis of the context, site and building design potential and a road map of possible design strategies.

**Phase 2: Development of design concept.** Through the sketching process architectural ideas and concepts, functional demands as well as principles of construction are linked to energy and environmental building concepts and indoor environment through application of the design strategy. Different conceptual design solutions are developed and their relative estimated merits are continuously evaluated, including architectural qualities, against the goals in the building design brief. The outcome is an integrated building concept.

Figure 6a: Design Process for the Concept Design Phase of Responsive Building

**Phase 3: System design and preliminary performance evaluation.** In the system design phase the building concept develops into specific architectural and technical solutions and systems through sketches, more calculations and adjustments. Architectural, space and functional qualities, the construction and demands for energy consumption and indoor environment converge in this phase. The basic building form and its site location are determined after a series of functional analysis, design strategy step 1. At the same time by applying step 2-4 in the design strategy, a frame of responsive design is built considering various ideas of integration of passive- and active systems as reflected in the design concept explicitly with consideration of RBE’s and renewable energy technologies.

Figure 6b: Design Process for the System Design Phase of Responsive Building

**Phase 4: Component design.** In this phase after the performance of system design is confirmed, the final design will be completed. Here technical solutions are refined and design documents are created including final drawings and specifications in cooperation with building companies, suppliers and product manufacturers. The outcome is a comprehensive description of the entire project.
Phase 5: Operation and management. Many energy problems can be traced to a conflict between building services and many conflicts between services are control issues. An energy efficient design strategy should overcome this and the underlying reasons for conflict should be identified and eliminated to prevent carrying a flawed design forward.

5 Acknowledgement

The content of this paper is based on a recently completed research project (IEA ECBCS Annex 44), which has dealt with these issues and three publications addressing the challenges can be downloaded from the IEA ECBCS website (www.ecbcs.org/annexes/annex44.htm):

- Designing with responsive building components – an expert guide for rethinking new buildings.
- Responsive Building Elements – Expert Guide part 2

6 References


IEA-ECBCS Annex 44 “*Integrating Environmentally Responsive Elements in Buildings*”

www.civil.aau.dk/Annex44
1 Introduction

Heat pumps offer the possibility of reducing energy consumption significantly, mainly in the building sector, but also in industry. The second law of thermodynamics shows the advantages: While a condensing boiler can reach a primary energy ratio (PER) of at best 105 % (i.e. the boiler efficiency; the theoretical maximum would be 110 %, based on the lower calorific value), heat pumps achieve 200 % and more.

Whereas the thermodynamic principle of the heat pumping process was found at the beginning of the 19th century (by Carnot, Kelvin, and others), it was realized about 1834 (by Perkins and Evans) for refrigeration, and not before 1855 for producing heat: In this year, Peter Ritter von Rittinger put into operation the first heat pump, an open-cycle mechanical vapour recompression (MVR) unit, directly driven by hydro energy, in the saltern of Ebensee, Upper Austria. Much later, also the closed vapour process was used for generating useful heat. Essentially after World War II, heat pumping units for air conditioning of homes and individual rooms became common, somewhat later the “reversible” units for cooling/dehumidifying as well as heating, and after the oil price crisis of 1973 also the heating-only heat pumps for moderate and cold climates were introduced.

In Japan and in the USA reversible air/air air conditioning units are called heat pumps. Chillers for air conditioning purposes are more or less always called chillers, even if they are reversible and used as heat pump chillers producing useful heat. MVR (Mechanical Vapour Recompression) systems are practically never called heat pumps, as many other industrial application in the oil or in the food industry. In Europe the term heat pump was used in the beginning for heating-only units with the heat sources outside air or exhaust air from the ventilation system, ground and ground water, combined with hydronic heat distribution systems.

2 Applications

The general term heat pumping technologies is used for processes in which the natural heat flow from a higher to a lower temperature level is reversed by adding high value energy, i.e. exergy. The main applications are presently refrigeration and air conditioning, where useful “cold” is produced. The term heat pump is used for a unit producing useful heat. In Japan and in the USA reversible air conditioning units are called heat pumps. Chillers are more or less always called chillers, even if they are used as heat pump chillers producing also useful heat. In Europe the term heat pump is used for heating-only units with the heat sources outside air or exhaust air from the ventilation system, ground and ground water, combined with hydronic heat distribution systems [Gilli, Halozan 2001].
Taking different applications of heat pumping technologies several items have to be taken into consideration like drive energy, design of the unit, integration into a system and control strategy:

- The drive energy of heat pumps is most commonly electricity, and for the future improved power generation systems based on renewable and fossil fuels have to be taken into consideration. The power plant efficiency is up to 58 % for gas-fired combined-cycle power plants available on the market; with oil as fuel similar values are possible. The power plant efficiency depends, of course, on the kind of fuel (primary energy source). PER, the primary energy ration, is highest for direct power generation from renewable sources such as hydro or wind, for which the power plant efficiency \( \eta_{PP} = 1.0 \) by definition. PER gives an absolute measure of the units of useful cold/heat obtained from one unit of primary energy at power plant input, neglecting for the moment losses upstream of the power plant such as in production, cleaning, transmission, and distribution losses between power plant and heat pumping equipment. For absorption heat pumping units, PER is the ratio of cold/heat output to primary energy input (not to the power plant but to the heat pumping units).

- The second item is the efficiency of the unit, which is most commonly expressed by the COP, the coefficient of performance. This COP depends on the refrigerant selected and on the components used like the compressor, the size and the design of condenser and evaporator, the flow sheet – single stage, two stage, economiser or cascade – and the internal cycle control. The choice of the refrigerant is most commonly a compromise between efficiency and cost, smaller equipment using a high-pressure working fluid can reduce the cost, a working fluid with low discharge temperatures can avoid a two-stage system.

- The third item is the integration of a unit into a system, and again the choice of the refrigerant may have a large influence on this integration. The most efficient way of heat absorption/heat dissipation is direct evaporation/direct condensation; the alternative are secondary loop systems. Secondary loop systems require an additional temperature lift to transport heat to the evaporator and from the condenser, and most commonly they require circulation pumps with an additional power consumption. Especially in low-temperature applications this may cause problems. This means that secondary loop systems are less efficient than direct evaporation/condensation systems.

However, the unit itself can be designed as a compact unit and the refrigerant content can be minimised. Additionally, if heat absorption/heat dissipation happens in spaces with public access, the working fluid has to be a safety refrigerant, flammable and/or toxic fluids cannot be used. But there are lot of applications, where the secondary loop system already exists, for example hydronic heating systems or cold water based air conditioning systems. In large cold stores the use of direct systems with flammable and/or toxic working fluids is also possible.

- The fourth item is now the real operation of the system combined with the control strategy selected, and the operation of the system shows not only full-load, but mainly part-load: many systems loose a lot of efficiency operated in part-load, and taking this part-load operation one will get the SPF, the seasonal performance factor, which includes the cold/heat output, the drive energy at the different operating conditions, and the parasitic energy consumers like fans and circulation pumps. This is the value which has to be taken into account when specifying the TEWI; such a figure is too complicated for a politician and for an environmentalist. But this figure is a basis for the right selection of the whole system [Halozan 2002].
3 Possible Future Development

The future development will be characterised by the improvement of components, probably other refrigerants, and advanced systems in advanced buildings and communities.

3.1 Technological Development

In the small to medium size capacity range the reciprocating compressor has been practically replaced by the rotary compressor and the scroll compressor. A new development are small centrifugal compressors with high-speed drives and magnetic bearings for oil-free operation.

Liquid/refrigerant heat exchangers have changed to welded flat plate heat exchangers, for air/refrigerant heat exchangers multi port micro channel heat exchangers become more and more interesting.

Ground-coupled heating-only heat pumps, especially direct-evaporation systems in Europe, have increased their SPF to 4 and lately up to 5. Besides better components, improved building codes with the possibility of reducing supply temperatures required to values below 35°C are responsible for this development.

For larger systems for both heating and cooling the ground is used as a store. Additionally low-ex systems, i.e. high temperature cooling and low temperature heating systems, can contribute for increasing the system efficiency significantly.

3.2 Refrigerants

The refrigerants (working fluids) from 1834 up to the 1930s were ammonia, carbon dioxide and other fluids, most commonly toxic and/or flammable; later on the “safety refrigerants” (chlorofluorocarbons, CFCs, and hydrochlorofluorocarbons, HCFCs) quickly occupied the market, and the old refrigerants disappeared from the market. The only exception was ammonia, it was and still is in use for large applications. This situation remained so until at the Vienna Convention of 1986 and the Agreement of Montreal 1997 the future production of CFCs was limited and in the end essentially banned, for reasons of destroying the stratospheric ozone layer. A few years later (Kopenhagen, 1992) also an agreement for limiting the HCFCs was concluded, a phase-out schedule until 2030 - in the EU until 2015 – already exists. In some countries even more rigid phase-out schedules have been decided, the EU will phase out R134a for automotive air conditioning, Denmark, Switzerland, and Austria want to phase out HFCs due to their global warming potential. Alternatives are ammonia (R-717), the hydrocarbons propane (R-290), sometimes propylene (R-1270) or isobutane (R-600a), water (R-718) and CO2 (R-744). Ammonia and the hydrocarbons do not match the requirements of a “safety” refrigerant caused by toxicity and/or flammability; water and CO2 keep it (Halozan, Rieberer 2006).

Ammonia – R-717: The technology used for ammonia systems is different from the technology used in systems with fluorocarbons: Copper is not compatible with ammonia, one has to use steel or aluminium, and steel has to be welded, aluminium welded or soldered, but soldering aluminium is more difficult than soldering copper. The problem of ammonia units is the combination of all these differences. For large systems within an industrial process, mostly in the chemical, food and lumber industries, this is not a serious problem. The real problems are medium sized and small applications, where ammonia is in competition with direct evaporation/condensation systems. Nevertheless, ammonia has an increasing share in new equipment, developments are going on to introduce hermetic ammonia compressors.

Other developments are to reduce the refrigerant charge of the systems. The one change was from flooded evaporation to dry evaporation, the second was in the case of small systems the change from non-soluble oil to a soluble oil. Combined with flat-plate heat exchangers the refrigerant charge has
been reduced significantly (0.1 to 0.05 kg/kW heating capacity). Such units are used for cold stores as well as for retail refrigeration, direct evaporation systems have been changed to systems with a secondary loop. For higher temperatures 40-bar compressors with maximum condensing temperatures of more than 74°C have been developed [Halozan 2005].

Propane – R-290: Compared with existing units using R-22 as refrigerant, only a few changes have to be made to adapt the unit for the operation with propane, to improve the performance of the unit an internal heat exchanger has to be added, and the COP of the unit becomes significantly higher. Furthermore, the condensing temperature can be increased from 57°C of a R-22 unit to 65°C of the propane unit.

CO2 – R-744: Presently CO2 is being used as heat carrier in commercial secondary loop systems. But with CO2 it is also possible to realise again direct evaporation systems by using it as refrigerant in the low-temperature stage of a refrigeration cascade.

For applications with condensing temperatures exceeding 30°C the trans-critical cycle, also proposed by the late Prof. Lorentzen, with pressures up to 140 bar has to be used. This cycle is characterised by evaporation taking place in the sub-critical region, whereas heat rejection takes place in the super-critical region. Taking the temperature-entropy-diagram this happens near the critical point. This means a heat rejection characteristic similar to the Joule-Brayton cycle, but in a region with strong deviations from ideal gas conditions; the maximum of the specific heat - infinite in the two-phase region and at the critical point - is still existing [Rieberer 1998].

Highly efficient solutions using CO2 are hot water heaters, air heating systems and exhaust air heat recovery systems suitable for being the only heating devices for ultra low energy and passive houses, respectively [Halozan, Rieberer 1999].

H2O – R-718: Water has been and is being used successfully in MVR systems; but nowadays it is also used for chillers where the water is both refrigerant and heat carrier. Due to the low volumetric cooling capacity centrifugals have to be used, and the smallest capacity presently realised in prototype installations is about 800 kW.

3.3 Systems

The most important item is the development of systems. The interaction of the user, the building, the heating/cooling equipment and the control has to be considered very carefully, and only such a system approach can achieve highly efficient systems. One example are ground source heat pump systems (Fig. 1). Special highly efficient solutions are direct exchange ground source systems (DX systems), which are mainly used for horizontally installed ground collectors, or vertically installed secondary loop systems using a CO2 thermo siphon [Halozan, Rieberer 2002]. Other examples are low-ex systems activating the building structure for base load heating and cooling and hybrid systems, where dehumidification is carried out by DEC – desiccant evaporative cooling – systems.

A further step has been already realised in the so called passive houses: The transmission losses through the building envelope are in the range of 15 W/m². The next step was the introduction of controlled ventilation combined with an exhaust air heat recovery system (Fig. 2).
By means of heat exchangers ventilation losses can be reduced by 50 to 90%, depending on the type of heat exchanger used. However, heat exchangers can only reduce the ventilation load, they cannot be used for heating purposes.

With heat pumps the ventilation losses can be reduced also; additionally they can be used for heating purposes, because the fresh air temperature can be increased to a level higher than the indoor temperature. However, in contrast to heat exchangers an energy input is required.

The optimum solution is the combination of both, a heat exchanger and a heat pump. The exhaust air is firstly cooled down in the heat exchanger and then used as heat source for the heat pump; the fresh air is preheated in the heat exchanger and then further heated by the heat pump. Such houses can be heated down to low outside temperatures by the ventilation system alone, the remaining heating demand can be covered by electric resistance heating, but it can also be covered by further reducing the heat load.

For larger systems even more efficient solutions are possible using heat pumps (see Fig. 3).

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**Fig. 1: Ground Coupled Heat Pump System**

**Fig. 2: Passive House Heating/Cooling/Hot Water System**

- By means of heat exchangers ventilation losses can be reduced by 50 to 90%, depending on the type of heat exchanger used. However, heat exchangers can only reduce the ventilation load, they cannot be used for heating purposes.

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For larger systems even more efficient solutions are possible using heat pumps (see Fig. 3).
In this system the ground is used as a store and the heat pump is used for direct cooling at the beginning of the cooling season, for simultaneous heating and cooling, where heat is shifted from the cooling side of the building, caused by solar radiation or high internal gains, to the heating side of the building, and for heating. The ground as a store allows high heat source temperatures at the beginning of the heating season and low heat sink temperatures at the beginning of the cooling season, peaks, which are common in an outside air system, will not occur in such a system.

4 Heat Pumps and the Energy System

Heat pumps have to be considered as part of the energy system. The fuels we use are more or less exergy, however, the amount of exergy we need in the energy used in buildings is small. Indoor air with a temperature of 21°C at an outdoor temperature of 0°C has an exergy content of 7%. Providing this temperature with fuels means using at least 100% exergy, in the case of the heat pump it is theoretically 7%, in practice due to heat transfer, expansion and compression losses 15 to 20%.

4.1 Efficiency

Figure 4 demonstrates the efficiencies of thermodynamic heating/cooling. The coefficient of performance (COP) is shown at the right-hand scale: COP = Q/Ex. The internal efficiency is given by the ratio η = COP/COPideal at △T. The left-hand area refers to cooling: freezing, refrigeration and air conditioning including dehumidification, the right-hand area refers to heating: The heat pump area shows a temperature lift of 5 to 70 K, Ex/Q is between 0.08 and 0.45 and COP therefore between 2.2 and 12.5, the efficiency η is about 0.4...0.7. The important term for the COP is △T, the temperature lift in the heat pump. This △T depends on the temperature of the heat source, which can be increased by using the ground as heat source instead of ambient air, and by the temperature required by the heat sink. In highly insulated buildings with floor heating systems this temperature can be reduced to values below 30°C, so △T can be reduced to 20 K. The coefficient of performance of the area “Cogeneration” is different: Here the real exergy loss is smaller than the theoretical one because of reduced turbine losses and condenser losses.

Over the (positive or negative) effective temperature lift △T from ambient, the relative exergy E/Q is plotted for the ideal process (Carnot process, second law of thermodynamics) and for real processes. For the ideal process:

\[
\frac{E_x}{Q} = 1 - \frac{T_a}{T} = \frac{T - T_a}{T} = \frac{\Delta T}{T} = \eta_c
\]

where

- \( E_x \) Exergy
- \( Q \) Heat transferred
- \( T_a \) Ambient temperature, K
- \( T \) Process temperature, K
- \( \eta_c \) Ideal (Carnot) efficiency

Figure 4: Ideal and real power consumption \( E_x/Q \) for cooling (freezing, refrigeration, air conditioning) and space heating by heat pumps and by cogeneration district heating
4.2 Performance

The drive energy of heat pumps is most commonly electricity, and for the future improved power generation systems based on renewable and fossil fuels have to be taken into consideration. The power plant efficiency, $\eta_{PP}$, is up to 58% for gas-fired combined-cycle power plants available on the market; with oil as fuel similar values are possible. The power plant efficiency $\eta_{PP}$ depends, of course, on the kind of fuel (primary energy source).

Table 1 shows the relations for the more important primary energy sources and for heat pump SPFs of 4 and 5. PER is highest for direct power generation from renewable sources such as hydro, wind or solar, for which I still look about your paper. Is it possible to change the text in the diagrams from time new roman into $\eta_{PP} = 1.0$ by definition. More information than by PER is, however, given by comparing, for a given fuel (primary energy source), the efficiency of the indirect path via power plant and heat pump (PER) to the efficiency of the direct path of conversion ($\eta_B$), e.g. in a heating boiler. The ratio may be called Useful Energy Ratio $UER = \frac{PER}{\eta_B}$. Comparing the same fuel means that all upstream effects cancel each other out.

Table 1: Typical Primary and Useful Energy Ratios

<table>
<thead>
<tr>
<th>Efficiencies</th>
<th>Coal, Biomass</th>
<th>Gas</th>
<th>Renewables</th>
<th>Nuclear</th>
</tr>
</thead>
<tbody>
<tr>
<td>PER: SPF = 4</td>
<td>$\eta_{PP}$</td>
<td>0.4</td>
<td>0.55</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>Boiler (local conversion), $\eta_B$</td>
<td>0.8</td>
<td>0.98</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>PER = SPF. $\eta_{PP}$</td>
<td>1.6</td>
<td>2.20</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>UER = PER/$\eta_B$</td>
<td>2.0</td>
<td>2.24</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>PER: SPF = 5</td>
<td>2.0</td>
<td>2.75</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>$\eta_{PP}$</td>
<td>2.5</td>
<td>2.81</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>UER = PER/$\eta_B$</td>
<td>2.5</td>
<td>2.81</td>
<td>5.0</td>
</tr>
</tbody>
</table>

The data of Table 1 show that boiler efficiencies near 1.0 are close to the theoretical limit (i.e. for the gas-fired condensing boiler). A SPFs of around 5.0 is far below the theoretical limit of heat pumps; SPFs of 6 or more may be possible and will be economic in the future.

4.3 Renewable energy gain by heat pumps

It should be noted that the heat pump, which in most cases grades up free heat from the environment (air, water, ground) and from waste heat, is a major source of renewable energy. The renewable heat $R$ gained by the heat pump is the difference between the thermal output $Q$ and the drive energy $Ex$ (in the case of electricity, $E = Ex$):

$$R = Q - E = Q - \frac{Q}{SPF} = Q(1 - 1/SPF)$$

Obviously, if the drive energy is electricity from renewable sources, all the energy used for the heat pump is renewable energy. One example are photovoltaic driven compression systems.

Another type of systems are thermally driven heat pumps, mainly gas-driven absorption heat pumps. But thermally driven systems can also use solar thermal, heat from CHP plants, district heat and heat from biomass.

5 Conclusions

Heat pumps are an old technology, which has not been extensively used as long as both energy prices and the efficiency of electricity generation have been low. The oil crises have changed this situation, and now Kyoto is a further reason for the increasing market deployment of this technology. Based on recent developments, the following conclusions can be drawn:
Heat pumps offer the possibility of reducing energy consumption significantly, mainly in the building sector, but also in industry. Basic second law thermodynamics show the advantages: while a condensing boiler can reach a primary energy ratio (PER) of 105 % (the theoretical maximum would be 110% based on the lower calorific value), heat pumps achieve 200% and more, with hydro or wind energy even 400 % and more.

The drive energy is most commonly electricity, and for the future improved power generation systems based on renewable and fossil fuels have to be taken into consideration. The efficiency of gas-fired combined-cycle power plants available on the market is presently about 58 %, with oil as fuel similar values are possible. Ground-source (“geothermal”) heat pumps combined with low-temperature heat distribution systems achieve seasonal performance factors (SPFs) of 4 and higher, which means PERs of 220 to 280 %.

Sorption systems - absorption, adsorption and DEC systems - also gain importance. Solar Thermal Cooling and Tri-Generation are based on sorption – absorption, adsorption and DEC units. The efficiency of sorption units has been improved significantly by introducing welded flat plate heat exchangers for reducing heat transfer losses, two-stage and GAX cycles.

With highly efficient systems the advantages of thermodynamic heating and cooling can be demonstrated and used for reducing the energy demand significantly.

The potential for reducing CO2 emissions assuming a 30 % share of heat pumps in the building sector using technology presently available is about 8% of the total world-wide CO2 emission. With advanced future technologies in power generation, in heat pumps and in integrated control strategies up to 16% seem to be possible. Therefore, heat pumps are one of the key technologies for energy conservation and reducing CO2 emissions.

References


1 Introduction

To avoid climate change and decrease global warming rate crucial strategies have to be undertaken. This includes improving the efficiency of the energy systems, reduction of primary energy demand and increasing the use of renewables. For this, the concept of exergy analysis or second law analysis is extremely helpful.

According to the second law of thermodynamics, the conversion of energy from one form to another is not always reversible. While the system is transferring into thermodynamic equilibrium, just a specific part of energy, called exergy, can be converted to work and the rest appears in the system as heat. The exergy evaluation considers the real thermodynamic efficiency of the system.

Since many years, the utilization of exergy is spreading more and more in different fields of energy systems. Recently, the term “LowEx” has been established in the building sector. A LowEx building has low exergy demand. The reduction of the exergy demand of heating and cooling systems can be achieved by efficient heat and cool generation (e.g. heat pumps), by the use of available temporal or spatial temperature potentials and by storage as well as by heat exchange processes with low temperature difference.

Several research projects are focused on the development of new heating and cooling systems with higher efficiency, on increasing the usage of regenerative and natural energy sources. This present investigation is focused on dynamic exergy analysis and new components for LowEx building.

2 Dynamic exergy analysis

Exergy is defined as the part of energy that can produce work while the system is transferring into thermodynamic equilibrium. Simplified, exergy expresses the quality of energy, showing how much work can be achieved using that specific amount of energy. It is a very important property of energy that it depends on the state functions of the system such as temperature. Therefore, exergy is evaluated with respect to a reference environment and the properties of the reference environment influence the exergy amount of the system. An exergy efficiency analysis of the system does not consider the system as an isolated unit but also considers its local reference environment.

The important role of the reference environment manifests itself in the calculation of exergy demand. The exergy amount of heat can be expressed as follows [Baehr 2005]:

\[ \dot{E}_Q = \left(1 - \frac{T_{\text{Ref}}}{T} \right) \dot{Q} = \dot{Q} \eta_{\text{Carnot}} \]  \hspace{1cm} (1)
Using this formula the exergy demand of a building can be determined. As for the reference temperature, one can choose between a static approach, using mean temperature per month or of a year, and a dynamic approach which means applying the dynamic outside temperature in the calculation of the Carnot factor and integrating $\hat{Q} \cdot \eta_{\text{Carnot}}$ over the time.

Figure 1 shows the simulation result of the exergy demand of a building in a heating period. The static method which uses the yearly mean temperature leads to almost the same exergy demand in January, February, March, November and October. Applying the monthly mean temperature leads to similar results as the dynamic approach.

The static exergy analysis can be used when there is a clear relationship between the environment temperature and the energy flow which covers the demand of the building, for example for the heating period this relationship is present. At cold days the heat demand flow is higher than the warm days. But it has to be noticed that there are heat sources independent from the reference environment such as internal loads and solar radiation. If they have a high contribution in reducing heat demand, the difference between the results of dynamic exergy calculation and static exergy calculation will be considerable. Figure 2 shows simulation results of the Carnot factor and the heat demand flow of two office rooms with same dimensions and same user profiles but different orientations. Dispersion of the values for the south oriented office room is higher due to high solar gains. The exergy demand calculated via the static method is about 13% lower than the exergy demand estimated by the dynamic method.

The same diagram for the cooling period becomes even more scattered (See figure 3). In this case the contribution of the solar gains and internal loads is higher therefore the relationship between demand and Carnot factor, or better say demand and temperature, is not visible anymore.

In this case the exergy demand for cooling calculated with mean reference temperature is about 5-15 % higher than the demand calculated using dynamic methods. The static approach of exergy evaluation can hardly be used for cooling systems.
Figure 2: Heat flow vs. Carnot factor for two office rooms with different orientation.

Figure 3: Cooling power vs. Carnot factor for two office rooms with different orientation.
3 Exergy evaluation of different heating systems

The concept of exergy in evaluating systems can have two main applications: Firstly for each component the exergy efficiency can be calculated. This means exergy losses can be identified and prevented. Secondly the overall exergy efficiency can be determined.

Defining characteristic exergy values helps to have a measure to compare system with each other:

\[
\kappa_{\text{Generation}} = \frac{\dot{E}_{\text{L,Generation}}}{\dot{E}_{\text{Demand}}} \\
\kappa_{\text{Transport}} = \frac{\dot{E}_{\text{L,Delivery}} + \dot{E}_{\text{L,Distribution}}}{\dot{E}_{\text{Demand}}} \\
\kappa_{\text{Overall}} = \frac{\dot{E}_{\text{Input}}}{\dot{E}_{\text{Demand}}}
\]

Characteristic exergy values are defined to determine the exergy efficiency of the system. Exergy figure of generation and heat transport can provide a component based evaluation. Exergy demand
expresses the exergy efficiency of the building. The overall efficiency factor decides whether the considered system is a LowEx system or not.

The table 1 shows the exergy figures of two simulated heating systems: heat pump and boiler. Both systems use floor heating for heat delivery in the room. Exergy demand of the building in both cases is the same. The low exergy figure of generation in the heat pump system is explained by the application of geothermal energy. On the other hand this system has higher distribution losses because of the higher hydraulic losses in pipes between the heat pump and the building. The exergy figure of generation is high in the boiler system due to high exergy losses in combustion. The exergy of fuel used in this case (gas) is much higher than the exergy amount of the produced hot water.

Table 1: Exergy figures of two different systems: heat pump and boiler.

<table>
<thead>
<tr>
<th></th>
<th>Exergy figure of generation</th>
<th>Exergy figure of heat transport</th>
<th>Overall efficiency factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler</td>
<td>21</td>
<td>3,1</td>
<td>26</td>
</tr>
<tr>
<td>Heat pump</td>
<td>8</td>
<td>4</td>
<td>12</td>
</tr>
</tbody>
</table>

The main aim in low exergy systems is to reduce the exergy demand and substitute the input exergy of the system with anergy: the environmental energy such as solar energy or geothermal energy. In such buildings innovative strategies can be used to reduce the exergy demand. We introduce two high temperature cooling systems which can lead to LowEx buildings.

3.1 Heat displacement

Inside many buildings there are large differences of the heat loads between rooms or zones of a building (for example server rooms vs. corridor). These differences cause different temperature zones inside the building. The variability of the thermal loads is caused by the building orientation, internal heat loads and the air exchange rate. The heat loads differ concerning the absolute values as well as the temporal characteristics. Special situations can be found in server rooms or highly occupied offices. During many hours of a year some parts of a building have to be heated and other parts have to be cooled at the same time. Rooms with higher temperatures can be used to heat up rooms with lower temperature levels.

The thermal performance index rates the transferred energy between the test and the reference room related to an ideal process. The equation (5) shows the calculation of the ideal thermal system performance:

$$\dot{Q}_{\text{Transfer,ideal}} = \frac{\dot{Q}_{\text{Load1}} - \dot{Q}_{\text{Load2}}}{2},$$

(5)

where $\dot{Q}_{\text{Transfer,ideal}}$ is the ideal value of the heat transfer between the room 1 with $\dot{Q}_{\text{Load1}}$ and the room 2 with $\dot{Q}_{\text{Load2}}$. The measured performance is referred to the highest possible performance giving the relative transfer power $\psi$. 

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The relative transfer power depends on the dimension and the direction of the heat exchange area as well as on the direction of the heat flux. Figure 5 represents the relative transfer power for different combinations of activated room surfaces. This room has two façade heat exchangers but no internal loads but it is connected to another room with an internal load of 34 W/m². Both rooms are equipped with capillary pipe mats. The evaluation of the measurement data gives a higher value of thermal performance index in cases of an activation of all capillary pipe mats in the room. The activation of separate surfaces decreases the thermal performance index.

Figure 5: Relation between the measured and the theoretical performance for different combination of activated room surfaces.

It has to be noticed the system performance is dependent on the area of the activated capillary pipe mats. In this case relative transfer power is higher when only separated capillary pipe mats are activated. The activation of all room surfaces shows the lowest performance referring to the total surface area for the heat exchange process.

**Heat transfer to the ambient air**

In many buildings there are temperature differences between the room air temperature and the ambient air. Rooms with high thermal loads may also have a cooling demand at low ambient air temperature especially if there is no possibility of natural ventilation.
Therefore a transfer of heat to the ambient air with a façade integrated heat exchanger can reduce the room temperature. Some experiments have been done with capillary pipe mats which absorbs heat from the room. The warmed water will be recooled in the façade heat exchanger. The cold water is transported back to the capillary pipe mats and can be heated again.

Some experiments for heat transfer have been done. The temperature difference between the ambient air and the room air is the potential for heat transfer process. A higher temperature difference increases the cooling power. The temperature potential is usually highest during night time. Figure 6 shows an increasing cooling power at higher temperature differences between the room air temperature and the ambient air temperature.

Figure 6: Cooling performance referring to the outside air temperature.

Figure 7: Performance in W/m² depending on the temperature difference between the room air and the ambient air.
The activation of single room surfaces for the cooling process causes a reduction of the cooling power because of the smaller area of heat transfer. In relation to the surface area of the capillary pipe mats the relative cooling power decreases with rising heat surface area.

Because of the better heat transfer at cooling ceilings this relation is the highest one if only the capillary pipe mats in the ceiling are activated. The activation of all areas leads to the lowest relative value. These aspects are shown in Figure 7.

The combination of a façade heat exchanger and capillary pipe mats shows a new possibility to use the temperature potential between a building and the ambient air. The thermal performance varies depending on the size of the heat transfer area, its dimension and the direction of the heat fluxes.

### 3.2 Phase changing materials for cooling in LowEx building

Utilization of latent heat storages in LowEx buildings becomes higher because of their low operation temperature. Figure 8 shows one approach to generate cooling power by applying ambient air as heat sink: The system which consists of a latent heat storage device (1) based on paraffin, large area heat exchangers (2) inside room surfaces and ambient heat exchangers (3). During daytime, when the office needs cooling, heat is withdrawn from the room air by a cooled ceiling. This cooled ceiling is built up by embedding capillary pipe mats inside the ceiling surface. The warm water coming from the capillary pipes is carried by a pump to the heat storage device. Inside the storage device the heat causes a phase change of the encapsulated paraffin. Since this melting process is endothermic, the water is cooled and can be returned to the inlet of the ceiling heat exchanger. The room may be chilled by this means until the whole paraffin containment of the storage device is melted. During night time, when ambient temperatures decrease, the controller unit switches to another hydraulic circuit and invokes a pump in order to transport warm water from the heat storage device to the ambient heat exchangers. The heat is then released via thermal radiation and natural convection to the ambient causing the paraffin inside the heat storage device to solidify again.

![Figure 8: Case study: room cooling based on heat storage device (1), large area heat exchanger (2, overemphasized for illustration purposes) in the ceiling and ambient heat exchangers (3).](image)

Figure 9 shows a measured daily curve of mass specific thermal power of latent heat storage in combination of capillary pipe mat installed in a room. In the period from 8.00 am to 6.00 pm the room was cooled by the latent heat storage. The rest of the day was used to regenerate the storage. The maximum measured cooling power is relative to the mass of the PCM at 19 W/kg. At the nightly storage regeneration phase the maximum power is at around 8 W/kg. Vacillating indoor air temperatures and different outdoor air temperatures have an impact on the performance and heat quantity of the system.
Figure 9: Daily curve of mass specific thermal power of the latent heat storage

Figure 10 shows the mass specific absorbed and the emitted heat of the latent heat storage for a period of seven days. Concerning the values displayed it should be pointed out that these do not simply represent the material properties of the PCM but that the measured values include the heat capacity of the storage body and the water inside the heat storage. Under these conditions an average heat capacity of 45 Wh/kg could be measured during the room cooling phase at daytime.

In the experiments an average temperature difference of the storage material between day and night of about ten Kelvin is measured. Compared with a pure water storage, the latent heat storage has got a fourfold higher heat capacity.

Figure 10: Mass specific absorbed and emitted heat of the latent heat storage.

Reduction of the room air temperature

The temperature measurements show that the used storage mass of 1.7 kg/sqm can reduce the room air temperature of up to 2.5 Kelvin. In addition to the experimental studies, numerical simulations of the experimental setup were carried out. Therefore the system is modelled in the modelling language.
Modelica. First simulation results with an increased storage mass of 8.0 kg/sqm show a possible temperature difference of up to 4 Kelvin between the two test rooms.

**Heat storage regeneration process**

Figure 11 shows the plots of the heat storage, room air and ambient air temperature. The phase change of the used paraffin is in a range from 20°C to 22°C. But the measured system temperatures exceed this range at day and undercut it at night. The system would work more efficiently if the storage temperature is within the range of the phase change temperature. To avoid this, there are two options for system improvement. One option is to increase the storage mass. On the other hand, after the complete regeneration of the store a direct cooling of the room by the façade integrated heat exchanger can be carried out. This is done by direct hydraulic coupling of the capillary tube mats with the heat exchanger. The measured temperatures of this experiment show a temperature difference between the two rooms of up to 4.0 Kelvin.

![Figure 11: Measured curves of the heat storage, room air and ambient air temperature.](image)

The results show for the test room with a latent heat storage a reduction of indoor air temperature up to 4 K, with a storage mass of 1.7 kg/sqm. This shows the fundamental capabilities of latent heat storages, with a melting temperature near to the room air temperature, for cooling applications.

**4 Summary**

The exergy analysis considers the quality of energy. The application of energy analysis in building sector is shows effective possibilities for system evaluation. A building is not an isolated unit. Its demand for heating or cooling is under continues change because of the fluctuating in environment state, solar effects and users’ behaviours. A dynamic exergy analysis considers these changes and provides a precise calculation of the exergy needed.

**5 References**

LowEx Houses: The Next Step in Energy Efficiency?

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Nowadays the building bound energy consumption of newly build houses has decreased dramatically in comparison to twenty years ago. On the contrary is the energy use of household appliances, PC- and home network systems and battery operated apparatus still increasing year by year. Through calculations it is shown that household appliances and lighting has a ratio of about 50% of the total primary energy use of a today’s new house where twenty years ago this ratio used to be about 20%. The other 50% consists of energy use for space heating and domestic hot water. This implies mainly that the type of energy carriers needed is changing from heat towards electricity.

In this presentation it is shown how a low-ex approach this changing need in energy carriers and how household appliances can be integrated within heating and cooling systems. In the mean time the differences with the passive house design strategy are given, especially with respect tot the household energy use.

In general the consequences for energy neutral district development are given for the approach of both low-ex and passive house.
COMMUNITIES I
Low Exergy Solar thermal supply for community based energy –Drake Landing as a working example

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Abstract

The process of heating buildings on a community scale using solar energy is discussed with reference to the Drake Landing Solar Community (DLSC) in Okotoks, Alberta, Canada. Operation of this 1.5MWt system is discussed with a view to the use of the thermodynamic term exergy as a discriminator for its operating conditions. The paper illustrates the impact of a low-exergy energy supply as it heats the 52 dwellings of the subdivision energy through the use of a district energy piping network. The district energy system incorporates short term and long term thermal storage to address the imbalance between the availability of thermal heating and the space heating demand of the consumers. The project is part of an ongoing research project that has yielded valuable data to compare operation under the original design conditions as well as under a revised supply temperature profile. By comparing the supplemental consumption of natural gas before and after the change in program in terms it becomes possible to develop an economic benefit of a lower exergy, lower supply temperature. These observations then provide insight into the practicalities of developing future solar community projects.

1 Theory

The climate in Canada requires that approximately 1480PetaJoules of energy be consumed annually to keep our residential and commercial buildings warm\(^1\). Forty percent of this energy stream comprises electricity, oil and other fossil fuels while 60% is natural gas that is combusted in furnaces, boilers and fireplaces across the country. Depending upon who you talk to, these furnaces and boilers vary in combustion efficiency from the mid-fifty percent range to a manufacturers claimed efficiency that exceeds 90%. However while these numbers suggest that this energy is consumed at a high degree of efficiency they fail to indicate whether the decision to use this energy stream for heating was indeed the right one for the user.

The use of exergy has been claimed by many to allow evaluation to be made of energy conversion processes, thereby providing the user with an understanding of the impact of each phase or activity in the process of transmission and thus the degree to which the quality of the energy stream degrades. Degradation, as the term implies reduces the ability for that energy stream to undertake useful work: the more that the initial quota of exergy is destroyed, in activities such as heat transfer then the more the user is losing the full potential of that supply.

\(^1\) http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/comprehensive_tables/index.cfm?attr=0
2 Exergy flowpath

As defined in many text books, exergy is a function of both enthalpy and entropy; a combination of the 1st and 2nd laws of thermodynamics. Its relationship with energy is established as:

\[
\frac{\text{Exergy}}{\text{Energy}} = (1 - \frac{T_{\text{operating}}}{T_{\text{supply}}})
\]

Where the term exergy is seen as a relative term in that both the energy and exergy relate to some reference condition \((T_{\text{ambient}})\), making the ability to undertake work dependant as much upon the conditions after the work has been completed \((T_{\text{ambient}})\) as to the initial conditions of the energy stream \((T_{\text{supply}})\). Change the end conditions and the ability to do work changes likewise. This dependency on an ambient condition is an important feature to remember if one proposes to use exergy in an industrial situation or as a comparator for technologies.

A common misinterpretation associated with the term exergy is that because nature operates at in a low exergetic environment then a high exergetic system is bad and an indication of wasted energy. The mantra becomes – low-ex is good: high-ex is bad. However, since exergy has no purpose other than to compare the work potential of an energy stream between its supply and end conditions it is equally possible to have low exergetic efficiency in a warm water district energy system as it is with a steam based network. Exergy losses relate more to the efficacy and methods of energy conversion than to its absolute value. What is important though in a community based analysis is therefore not the absolute level of calculated exergy but rather where the available exergy is used in passing from its starting point to its final ambient condition. It becomes a tool for technology selection.

In North America, the space heating requirements for residential and commercial buildings is conventionally provided using forced air circulation. Construction techniques support the use of ducting within the building’s walls to aid distribution of warm air throughout the building. Natural gas is burned, either in a furnace’s plenum to heat air directly or in a boiler to provide hot water of steam that in turn, heats an air stream. Hydronic heating, as practiced in Europe is less common and chiefly found in eastern Canada or the northern communities.

![Exergy Flowpath through residential heating](image)

Figure 1: Exergy Flowpath through residential heating
In the case of forced air circulation (figure 1) exergy is first destroyed in the combustion process (27%) and then lost in the plenum of the furnace when the combustion air is used to create lower temperature air for circulation through the building. When a steam or hot water system is employed the further opportunities exist for exergy degradation throughout the distribution process. The electrical power required for the fans, pumps, etc destroys more exergy through the combustion of more fossil fuel to produce the power. The useful exergy, namely that which actually enters the room (air at 40°C) is a relatively small portion of that at the original supply conditions.

Ironically, the use of exergy could improve if the gas is combusted with an open flame within the room and the gases of combustion mixing directly within the ambient air. However, temperature control, health and other safety concerns would normally prohibit such an approach.

3 Does exergy conservation really matter?

Is it a bad thing that exergy is destroyed rather than transferred to the room? In transferring thermal energy from one body to another, the degradation of exergy is a natural phenomenon and essentially unavoidable so long as a temperature differential exists. The challenge becomes one of how to minimise the losses while retaining the economics of energy transfer to the end user. The issue has been studied extensively from an ecological perspective where the environment is a system and where the by-products of one activity become the feedstock for the next. When dealing with energy transfer however, the lower the temperature differential then the larger the heat transfer components and the slower the process. In society’s urge for greater response and lower costs the systems approach has given way to the use of fresh “raw product”. Hence new lumber is used for the building industry rather than cleaning and recycling lumber from deconstructed houses. In the energy sector too, natural gas is used for each and every heating application rather than recovering and reusing heat rejected from other activities.

This economic scenario dominates when the global supply of primary fuel is limitless and arguments over exergy become largely an academic exercise. However, in conditions of supply uncertainty or economic fluctuation, energy supplies need to be managed and this will only be achieved if the market links the fuel price to other properties such as its value or quality. A triage process would ensue to compare options and decide upon the best use for a particular energy stream given the technologies available. In these situations exergy could become a powerful factor in deciding the prices paid by the customer for the energy.

4 Mechanisms to maximise exergy use

As described earlier, exergy can be used to describe the change in work potential of an energy stream as it moves through a process. The goal of any analysis would be to ensure that the exergy is put to good use rather than simply lost to the environment.

The analysis of a steam power system might suggest that the natural gas will lose 27% of its exergy simply because of the combustion process. A further 24% loss will occur as the boiler creates steam while in the steam turbine typically 37% of the exergy would be used to create power while a further 9% would be destroyed. On reaching the condenser 97% of the available exergy has already been used or destroyed. These numbers suggest that if fossil fuel is to be combusted then power generation at as high a temperature as possible, such as in a gas turbine must be considered the first step to energy recovery. Allowing the combusted gases to cool through the generation of steam removes approximately 50% of the fuel’s potential for work.
Replacing the use of natural gas with technologies such as solar energy reduces the starting temperature from more than 2000°C to 80°C or lower and hence the overall exergy available. While it eliminates the potential for power production it also avoids many of the losses inherent in the combustion and heat transfer.

Despite this shift to a lower exergy supply there often remains a need in renewable energy systems for fossil energy to augment the renewable supply of energy, for example in times of insufficient solar or wind. The Drake Landing project incorporates a gas boiler for this situation. The project however benefited from this by evaluating the opportunity for utilising the lower temperature energy supply from a solar thermal collector, coupling it with the need for building retrofits that accommodate the lower supply temperature. By lowering the supply temperature it was possible to measure the displaced fossil fuels and assess the “value” of the low-ex energy supply as that of the displaced fuel.

5 Outline of Drake Landing Solar Community

The Drake Landing Solar Community is an Energy Demonstration Project in Okotoks, Alberta. It was developed to demonstrate to the energy sector, public and the building community that large scale solar thermal projects were possible, practical and perhaps economically feasible. The first of its kind in North America, the project is heated by a district energy system that has been designed to store solar energy underground during the summer months and distribute the energy to each home for space heating needs during winter months.

The community of Okotoks is more than 1,000m above sea level, but has an average summertime temperature that exceeds 20°C. This allows for the installation of solar thermal collectors that are mounted to facing due south and set at an angle of 45°, to generate energy at a rate of almost 1.5MW.
At the outset, the design goal of the system was to develop 90% of the community’s thermal energy needs through the use of these panels.

Several issues needed to be addressed in the design for this to be possible. Firstly the demand for heating is rarely synchronous with the ability to collect it. Secondly the temperature demanded by conventional in-house distribution systems is often higher than would be collected on a continuous basis, and thirdly, it is sometimes difficult to locate the collection equipment adjacent to the user for reasons of installation and maintenance.

This latter point was demonstrated in California recently with their “Million Solar Roofs” plan where the installation and maintenance of the systems was found to be significantly easier if the panels, in this case photovoltaic panels, were co-located and separate from the housing complex.

To compensate for these modifications the community based solar thermal system incorporated short term and long term thermal storage, custom designed air handling units in each house and an independent district energy loop.

5.1 The Houses

The houses were built to the R2000 standard, a Canadian building standard that results in 30% less energy consumption than conventional practice. Each home is typically a 2-storey construction without a basement (slab on grade) and of approximately 142m² in heated area. The garages were separate from the house, designed and constructed to support the solar collectors. The array consisted of 800 flat plate solar panels that were organized as four rows as shown.

Figures 5 & 6 below show the collector panels on three of the four blocks of housing combining before the Energy Centre and the district heating piping installed as four separate loops.
During operation the heat transfer fluid is a mixture of water and non-toxic propylene glycol that is pumped to the solar collectors through underground, insulated piping ending at the community’s Energy Centre.

Once there, the heated solution passes through a heat exchanger, where the heat is transferred to the water in the short-term storage tanks (STTS). While the flow rate through the collectors is constant, the flow rate on the water side of the heat exchanger is automatically adjustable, allowing the control system to set a desired temperature rise.

5.2 The Energy Centre

The 250 square meter Energy Centre building is considered by many to be the heart of the district heating system. It houses the short-term thermal storage (STTS) tanks and most of the mechanical equipment such as pumps, heat exchangers, and controls.

Occupying most of the floor space are two large horizontal, insulated water tanks, each one 3.7m diameter and 11m long. Their size ensures water stratification and the improved efficiency of the system.
5.3 Bore Hole Energy Storage

While the short term storage copes with the daily energy variations, longer term energy storage is required and consists of borehole thermal energy storage (BTES). This underground structure charges during the summer months, possibly above 70°C only to be discharged during the winter. It consists of an array of 144 boreholes resembling standard drilled wells with plastic “U” tubes inserted and grouted to provide good thermal contact with the surrounding soil.

The storage tank borehole array is 37 meters deep and drilled on a grid of 2.25 meters. Overall, the field is 35 meters in diameter. At the surface, the U-pipes join together in groups of six, radiating from the center to the outer edge, and then back to the Energy Centre. As will be seen later the connection of the borehole piping is important to ensure the correct heating of the storage tank.

Figure 8: Plan of Borehole Thermal Energy Storage design

A separate set of PTEX pipes is used to distribute the heated water from the Energy Centre back to the homes. The hot water that circulates through these is typically between 40 - 50°C and well within the thermal limits of this commercial plastic piping. The distribution temperature will vary through the year based on the outside air temperature. The flow is regulated to match demands by the homeowners.
5.4 Air Handling

Circulating water at this lower temperature means that the losses are negligible. It also enables the solar collectors to operate in a more efficient manner, increasing the total quantity of heat available for delivery to the homes.

The unconventional supply temperature coupled with the demand for a large temperature drop through each air handling unit within each house necessitated a custom designed air handling unit. Each unit therefore included a heat recovery ventilator to ensure that indoor air quality is maintained and energy consumption is minimized.

In the event that solar energy is not available for an extended period of time and that the thermal storage is inadequate for the space heating requirements, a gas fired boiler is included within the design. It was considered at the outset that the need for the boiler would be limited to the winter months when the ambient air temperature fell below zero for several months.

The plant started operation in June 2007 and at that time it was estimated that to fully charge the underground storage to 80°C would take at least 3 years. At the time of writing construction of the 52 homes is complete and all homeowners have been installed since 2008. Monitoring is continuous and performance indications since May 2008 suggest that the solar energy system is performing as designed and that the 90% solar fraction will be achieved by year 5 (2012).

6 Exergy Performance

If the intent of this work is to use exergy to discriminate in favour of renewable energy technologies in replacing existing fossil fuel technologies then the debate will inevitably lead to the respective system efficiencies. The debate over whether a solar collector is more efficient at heating a room as opposed to a condensing gas furnace will raise the ire of many a heating contractor who fears for his or her job security. The use of exergy as a design tool at the community level must be associated with a very clear definition of what it is and what it means. It must also be unambiguous in its units and baseline conditions.
The performance assessment of the Drake Landing solar thermal collection system is therefore no different and will require several assumptions to be defined and accepted.

6.1 Source Temperature

Solar collectors can be used to demonstrate that sometimes renewable energy is not always low in exergy. As noted earlier, analysis would define the exergy input to a solar collector according to the equation

\[
\frac{\text{Exergy}}{\text{Energy}} = \left( 1 - \frac{T_{\text{operating}}}{T_{\text{supply}}} \right)
\]

Where Energy relates to the incident radiation falling on the panel and \(T_{\text{supply}}\) relates to the temperature of the sun, defined as 75% of that of a black body (Reference 5), ie

\[T_{\text{supply}} = 0.75 \times 5777 \, (K)\]

Using this temperature would clearly put the use of solar energy at a disadvantage when it comes to exergy efficiency. Fortunately a standardized approach to solar efficiency has been developed and collectors are tested according to known levels of incident solar flux.

6.2 Ambient temperature

The performance of heating and cooling equipment is assessed according to each community’s design temperature and these temperatures can fall to as low as -40°C in Swift Current in the south of Saskatchewan and probably also in parts of Europe. For Okotoks, Alberta the design temperature is -38°C. Using exergy calculations outside of the living room or laboratory will face dispute about the meaning of “ambient” since exergy performance is related directly to a temperature that is often taken as 20°C. Early research it should be remembered was based on the built environment where this temperature was a principal indicator of human comfort.

The ambient temperature is a key factor in the calculation of both energy and exergy efficiency for solar collectors. Energy efficiency and exergy efficiency are not synonymous since thermal efficiency relates to the quantity of energy extracted from the collector while exergy efficiency relates to the temperature of the collector (\(T_h\)). Both relate to the use of an ambient temperature (\(T_a\)), conventionally that of the surrounding air.

![Figure 10: Typical Exergy & Energy Efficiency Curves](image-url)
Figure 10 above demonstrates the impact of collector and ambient temperatures on efficiency.

The key factor is the difference between $T_{fi}$ (inlet temperature) and $T_a$ (ambient temperature). It is this ambient temperature that must be standardised if the process is to be compared against established fossil systems. Relating this to the ambient air temperature will result in the efficiency of performance varying throughout the season. As noted, in Alberta, the summer ambient temperature could reach 30°C while in winter the temperature could fall to -35°C. This degree of variation in ambient conditions adds confusion to any discussion on efficiency.

7 Value of low exergy operation

The design conditions for the original Okotoks project are illustrated in Fig 11 below. The solar collectors generate a heat source of 80°C that charges the short term thermal storage (STTS) to 75°C. The STTS tanks in reality are stratified and provide their excess heat to the borehole storage. Heating for the homes used extracted extract water from the STTS and passed through a heat exchanger to create a supply temperature according to the following program. This temperature would fall across the heat exchanger to maintain a room temperature (ambient) at 20°C.

The system design was created as an optimisation between the cost to construct the equipment and the comfort level of the residents within the 52 homes. Measured data from the system indicated a solar fraction that provided energy to charge the STTS sufficient to provide 60.4% of the annual energy (2008-2009) to the homes. The remaining 39.6% would be derived from back-up gas fired boilers attached to the system.

![Figure 11: DLSC Design Conditions](image)
In an attempt to increase the use of the solar energy collected, the supply temperature program to the district heating loop was altered twice, as shown in Fig 14 below. While the summertime set point was reduced marginally from 38 to 37°C the winter set point was reduced significantly from 67°C to 55°C and it point of initiation moved from 5°C to -2.5°C. This required negotiations with the homeowners who naturally considered that this new temperature would create drafts and be unable to heat their homes.
The net result of this was to increase the availability of solar energy during the winter months and reduce the natural gas demand. Revisiting the design conditions using the software Trynsys it has been possible to simulate the impact on the overall system that a reduced heating set point program would have. By using modelled environmental conditions it was calculated that over a 10 year period the consumption of natural gas reduced dramatically as the long term storage heated up and maintained its heat.

Figure 14: Heating Program Profile

Figure 15: Impact of supply temperature program and gas consumption
Table 1: Impact of supply temperature program and gas consumption (data)

<table>
<thead>
<tr>
<th>Year</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
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<td>1522</td>
<td>1057</td>
<td>901</td>
<td>828</td>
<td>801</td>
<td>773</td>
<td>745</td>
<td>736</td>
<td>728</td>
</tr>
<tr>
<td>Program 2</td>
<td>1278</td>
<td>373</td>
<td>184</td>
<td>122</td>
<td>94</td>
<td>77</td>
<td>66</td>
<td>57</td>
<td>51</td>
<td>47</td>
</tr>
<tr>
<td>Savings</td>
<td>302</td>
<td>1149</td>
<td>873</td>
<td>779</td>
<td>734</td>
<td>724</td>
<td>707</td>
<td>688</td>
<td>685</td>
<td>681</td>
</tr>
<tr>
<td>% saving</td>
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<td>75%</td>
<td>83%</td>
<td>86%</td>
<td>89%</td>
<td>90%</td>
<td>91%</td>
<td>92%</td>
<td>93%</td>
<td>94%</td>
</tr>
</tbody>
</table>

As shown in Fig 15 and Table 1, the revised “low exergy” supply program reduced the natural gas demand by 76% over that 10 year period and up to 94% saving in any one year. With a typical energy value\(^2\) for natural gas of $1.457/GJ this equates to a net saving of $ 10,668 (€ 8000). This is effectively the value of solar space heating, a value that reflects the level of investment needed in adapting the building heating system to accommodate the revised supply temperature.

8 Recommendations & Conclusions

The Drake Landing Solar Community was designed to demonstrate that solar thermal energy could be collected and distributed with sufficient efficiency to be used at the neighbourhood level. The measured results indicate that this is possible.

The project demonstrates too that in the application of low exergy systems there is a need to consider not only the source of the energy but also the final delivery system and the design of the building. The design of the air handling unit to accommodate the reduced temperatures was critical to the success of the project. As indicated through the reduction in heating supply set point, adequate heating is possible in a residential home and the saving in natural gas or supplementary fuel could make the project more economically viable.

The storage components of the system demonstrated the feasibility of seasonal storage with the boreholes reaching at least 76°C during the summer months.

To conclude therefore, the design of residential district energy systems is undoubtedly more complex than traditional fossil based systems but with the appropriate storage and distribution systems they can virtually eliminate the use of fossil fuels year round.

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\(^2\) Refers to the price of natural gas per GJ of energy and excludes any fixed charges associated with transportation, storage, administration, etc.
Exergy based Community Concepts and Energy Stations in practice: the EC REMINING-lowex project

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Keywords: low temperature resources, coal mines, European project, low exergy

Abstract

For the last 10 years numerous research and commercial initiatives have been undertaken in Europe in relation to development of the low temperature resources in coal mining fields. The most successful of them was the MineWater project in Heerlen, the Netherlands where low-temperature geothermal district heating system was launched on October 2008. Other projects are carried on in Germany, Scotland and some other European countries. Continuation of research on utilization of geothermal energy from abandoned mines is a goal of the 6th Framework Program project EC REMINING LOWEX Redevelopment of European Mining Areas into Sustainable Communities by Integrating Supply and Demand Side based on Low Exergy Principles. In project participate four local communities from the Netherlands, Slovenia Poland and Bulgaria. The project aims to demonstrate the use of locally available low valued renewable energy sources, specifically water from abandoned mines for the heating and cooling of buildings. The system is based on low energy principles, and is facilitated by an integrated design of buildings and energy concepts. Duration of the project is 5 years (2007-2012).

1. Introduction

Abandoned and flooded mines have a high potential for geothermal utilization as well as heat cold storage of water volumes in remaining underground spaces. The use of heat and cold from minewater is one of the important aspects of rational and sustainable utilization of post mining infrastructure and may bring positive socio-economic results, social rehabilitation and improved health for communities living in European areas with (former) mining activity. In Heerlen, the Netherlands, the redevelopment of a former mining area, including a large scale new building plan, is being realised with a low exergy infrastructure for heating and cooling of buildings, using minewater of different temperature levels as sustainable source. Mines have large water volumes with different temperature levels. In Heerlen the deeper layers (700 – 800 m) have temperatures of ~30°C; shallow layers (200 m) of 15...20 °C. These water volumes can be considered as heat/cold storage as well as geothermal sources. Most crucial however is that these sources provide low valued energy (low exergy). As on the demand side heating and cooling for buildings also require low valued energy the intended design strategy is to realise the climatisation of the buildings in this pilot preferably directly by minewater. The combination of low temperature emission systems with advanced ventilation technologies and integrated design of buildings and building services provide an excellent thermal comfort for 365 days a year, including sustainable heating and cooling and improved indoor air quality. This sustainable energy concept
The project is funded by EC Interreg IIIb, the UKR program of the Dutch ministry of Economic Affairs and the EC FP6 (CONCERTOII REMINING-lowex).

2. The energy concept

The minewater energy concept in Heerlen is in principle as follows. Minewater is extracted from four different wells with different temperature levels. In the concession of the former ON III mine (location 1 Heerlerheide) mining took place to a level of 800 m. In this concession the warm wells (~ 30 °C) can be found. In the former ON I mine (location 2 Heerlen SON) mining took place to a level of 400 m and here the relatively cold wells are situated. The extracted minewater is transported by a primary energy grid to local energy stations. In these energy stations heat exchange takes place between the primary grid (wells to energy station) and the secondary grid (energy station to buildings). The secondary energy grid provides low temperature heating (35 °C – 45 °C) and high temperature cooling (16...18 °C) supply and one combined return (20...25 °C) to an intermediate well.

![Image of schematic cross section of the underground conditions of the ON I and ON III mines]

Figure 1: Schematic cross section of the underground conditions of the ON I and ON III mines

The five well locations and energy stations will be connected by a three pipelines of 7 km each. Warm water is transported from the warm wells at the north and cold water is transported from the shallow wells at the southern region to the energy stations. Return water of 20...25 °C is transported to an intermediate well (450 m). The temperature levels of the heating and cooling supply are “guarded” in the local energy stations by a polygeneration concept existing of electric heat pumps in combination with gas fired high-efficiency boilers. The surplus of heat in buildings (for example, in summer, cooling, process heat) which can not used directly in the local energy stations can be lead back to the minewater volumes for storage. DHW is prepared in local sub-energy stations in the buildings by heat pumps, small scale CHP or condensing gas boiler, depending on type of building and specific energy profile. The total system will be controlled by an intelligent energy management system including telemetering of the energy uses/flows at the end-users. A scheme of the total concept is given in figure 2.
3. Integrated Design Approach versus traditional approach

The present development of energy efficient buildings in an increasing way requires an integral design approach. A couple of decades ago energy efficient design and building mostly focussed on improving a certain technique or apparatus. Nowadays an energy efficient building, supported by an energy efficient installation, has to be combined into one integrated energy efficient concept with an optimal performance in terms of indoor climate, thermal comfort, user’s satisfaction etc. This asks for an integral design approach in which well balanced choices are being made. This means that in sustainable building projects it is crucial to consider the design and realization of the sources, the heat generation (especially with non-traditional solutions such as heat pumps, cogeneration, heat/cold storage) distribution and emission together including all possible interactions with the building, building properties and building users. Only this approach can lead to a set of well defined performance criteria concerning energy performance, sustainability, indoor air quality, thermal comfort (365 days/year, winter and summer conditions), and health. Next to it is necessary to have specific emphasis on investments and energy exploitation, as well as communication to the end-users. A traditional approach is often based on partial optimization of the different disciplines. An integrated approach will achieve a total optimization, taken into account all disciplines and their interaction.

Basis is a set of unambiguous well defined performance criteria. The design strategy applied in this approach is the so called Trias Energetica. It is a three step approach that gives a strategy to establish priorities for realising an optimal sustainable energy solution, containing the following steps:

Step 1: Limitation of energy demand

Step 2: Maximizing share of renewables

Step3: Maximizing efficiency of using fossil fuels for remaining energy demand

With as overall prerequisite: limit the temperature levels of heat and cold supply (conform 2nd law of thermo dynamics).
In general the heating and cooling of buildings can be realized with very low valued energy, with medium temperatures close to required room temperatures. The better the building properties (extreme high thermal insulation, high air tightness and a suitable emission systems) the closer the temperatures of heat an cold supply can be to room temperatures. In order to utilise these extreme moderated temperatures for heating and cooling the buildings must comply to a number of boundary conditions such as:

- Limitation of heat losses ($U_{envelope} < 0.25 \text{ W}/\text{m}^2.\text{K}$, $U_{windows} < 1.5 \text{ W}/\text{m}^2.\text{K}$);
- Limitation of ventilation losses and peaks by air tight building ($n_{50} < 1.0$), mechanical ventilation with high efficiency heat recovery or state of art demand controlled hybrid ventilation systems;
- Limitation of solar and internal gains to limit cooling loads, integrating shading and sun blinds in architectural design;
- Application of combined low temperature heating and high temperature cooling emission systems, (thermally activated building components, floor and wall heating).

For some functions higher temperatures will be necessary such as domestic hot water. Also lower temperatures can be necessary for certain functions (high cooling loads for some types of buildings, dehumidification of supply air etc.). Another aspect to be taken into account is that the use of geothermal energy and heat/cold storage as such does not cover electricity use/sustainable electricity generation. Therefore additional sustainable solutions have to be taken into account. Sustainable electricity generation can be realized by cogeneration (such as biomass CHP). This combination can also deliver higher temperatures for DHW.

4. The demonstration locations

There are three main demonstration locations:

Heerlen Heerlerheide Centre

Heerlen centre SON (Stadspark Oranje Nassau)

Heerlen centre ABP head office

4.1 Location Heerlerheide Centre

This plan is situated on the concession of the ON III pit in a relatively deep mined area with warm wells ($30...35 \degree C$). The plans include the following activities for new buildings:

- 33.000 m² (330) dwellings (single family dwellings and residential buildings);
- 3.800 m² commercial buildings;
- 2.500 m² public and cultural buildings;
- 11.500 m² health care buildings;
- 2.200 m² educational buildings.

The first new building and construction activities in Heerlerheide Centre have started in 2006. The total plan will be realised between 2006 and 2011. All planned buildings will be connected to the energy supply (heating and cooling) from minewater. All buildings are planned in a very compact area which is very favourable for energy distribution. The building location is situated between two warm wells. Next to it, the planned building functions require heating as well as cooling. The energy supply includes the building of an energy station and a small scale distribution grid from this station to the buildings. In the energy station the minewater is brought to the necessary heating and cooling levels by heat pumps. In order to facilitate the process and to guarantee all real estate developers, involved in this building plan,
the delivery of energy to the buildings the main investor, Housing Corporation Weller, is realising the exploitation of the energy supply, including the building and construction of the energy station and distribution grid. It is important to realise, that with minor modifications this energy supply can also be functional and operational without the application of minewater.

Figure 3: Impression Heerlerheide centre with the completed mine water energy station

4.2 Location SON

The development of Stadspark Oranje Nassau has a strategic significance for the social and economical rehabilitation of Heerlen. This plan will be realized in combination with sustainable mobility and accessibility. The total programme contains the realisation of new buildings (110 apartments, 14,000 m² commercial buildings, 4000 m² hotel, 19,000 m² offices), the renovation of a large existing office building (43.500 m²) of the Dutch Central Office of Statistics (CBS) and the realisation of the new office building of CBS (21.000 m²). The new CBS office is completed in June 2009 and is connected to the minewater grid.
4.3 Location ABP head office

This location concerns the retrofitting of the ABP head office of 41,000 m². The total building envelope is retrofitted to a level better than the current Dutch Building Decree values for new buildings. The minewater will be used for comfort heating and cooling (i.e., low temperature heating and high temperature cooling in all offices). The ABP building will have a direct connection to the minewater wells and will have its own energy station to provide the required temperature levels for the distribution net. The energy station will have heat pumps. The emission systems in the offices are climate ceilings. Special glazing will be used to limit solar radiation in summer; this makes it possible to use high temperature cooling.
5. Balancing Supply and Demand side

For the elaboration of the final energy concepts following questions should be answered:

- total heating and cooling demand, how to control and limit this demand
- the target values for percentage of renewables in total energy demand
- what is the available amount of renewable energy from minewater (i.e. how much water can be extracted) and other renewables
- what is the most efficient conversion technology for the (not sustainable) back-up system.

This input is necessary for the integrated design process including buildings, sources and energy systems, distribution and emission systems.

An important tool for the assessment of this process and balancing demand and supply side is the so called energy profile of a building, expressed in a so called load-duration curve, based on dynamic calculations (using TRNSYS) of the energy demands of the buildings. This curve is a profile representing the energy demand over a total year, including heating and cooling.

This curve also provides a good indication of the maximal capacities for heating and cooling as well as the balance between heating and cooling demand. Important for balancing the supply and the demand side is the tuning and balancing between the cold and heat sources, in this case, the deep (warm) and shallow (cold) wells. This assessment takes place in relation to the required temperature levels, the yearly extracted volumes and the energy demands of buildings; this in relation to the available water volumes in the reservoirs. The load duration curves give important information about:

- the balance between cold and heat demands,
- the effect of optimisation (for example limiting heat losses by thermal insulation or heat recovery, etc.)
- the way how to limit the installed capacity of heat pumps, CHP and other heat generation, and, on the other hand, how to increase the number of operation hours, in combination with storage, to increase the efficiency and to decrease investment costs.

In order to establish a balance between the rational use of energy needs on the building side and the renewable energy supply a total annual heat-load duration curve of the total building plans in Heerlerheide Centre and SON is calculated by dynamic simulations with TRNSYS. In figure 11 the combined heat-load duration curve for Heerlerheide is shown.

![Figure 8: Annual load-duration curve Heerlerheide.](image)

The peak heating power is about 2.2 MW; this is about 20% lower than calculated with traditional heat loss calculations and can be explained by the internal gains and heat accumulation as taken into account only in the TRNSYS calculations. The four heat pumps in the Heerlerheide energy station will
have a combined peak capacity of 700 kWth and thus covering up to 80 % of the annual heat demand. Due to the small temperature step, the average COP of the heat pumps is ~ 5.6, but can raise up to 8 under favourable circumstances. A total heating capacity of 2.7 MW gas-fired condensing boilers will be installed as back-up and for peak moments (20 % annual). The heat-load curve also shows a period of ~ 2000 hours/year without any heating or cooling demand. The maximum cooling demand is ~ 1 MW and can be mainly covered by the minewater and inverted heat pumps. The heat and cold of the energy station are supplied tot the individual buildings by district heating. The supply temperature for the floorheating depends on the outdoor temperature and will be maximum 45°C at -10°C outside. The calculated seasonal average supply temperature will be 35°C and thus fit perfectly into the principle of 'very low heating". DHW is prepared by preheating the cold water with the supply for central heating and afterheated to 70°C with condensing high-efficiency boilers. In this way, the minewater heat pumps preheat about 30 % of annual demand for DHW (figure 12).

**Figure 9: Energy concept buildings Heerlerheide.**

All the dwellings at Heerlerheide will have floor heating and cooling. This requires good information to the habitants about the typical thermal behaviour of floor heating and cooling, including the restrictions on tapestry. The ventilation of all dwellings consists of mechanical supply and exhaust with high-efficiency heat-recovery (\( \eta = 90 \% \)). Commissioning of these systems is important to get properly functioning HVAC-systems under all circumstances. The lack of a infrastructure for natural gas forces the habitants to electric cooking, a non-traditional solution in the Netherlands.

### 6. LOW EXERGY DISTRIBUTION SYSTEMS

In Heerlen different solutions for distribution systems have been applied. In Heerlerheide Centre a central solution is applied with one central energy station where mine water is exchanged a post processed and a secondary distribution grid to the buildings. In the buildings there is a tertiary grid to for example to the apartment. A special feature in Heerlerheide is that apartments (social housing segment) have cooling.

In Heerlen Centre decentralised solutions are applied. In this part there are larger office buildings with their own energy stations where the mine water is exchanged and post processed, specifically to the building needs (which can differ to a large extent).
7. LOW EXERGY BUILDING DESIGN CONCEPTS IN PRACTICE TO USE LOW TEMPERATURE GEOTHERMAL SOURCES

In general the building design should be adapted to the use of the moderate supply temperatures for heating and cooling. This means limitation of transmission losses and ventilation losses and avoiding excessive peak loads. The latter is a special attention point for the ventilation and infiltration losses. This means the application of (advanced) controlled ventilation systems like balanced mechanical ventilation with heat recovery or advanced actively controlled natural ventilation systems. To avoid infiltration losses buildings should have a very good air tightness. Considering transmission losses the level of thermal insulation should be (in the Netherlands) better then the levels required by the building regulations (Dutch Building Decree) however, not on passive house level. In table 1 a summarised overview is given of the measures to make a building ‘mine water proof’ (i.e. lowex) for a moderate climate. It is crucial to design the buildings as ‘lowex’ as possible in order to be able to use direct heating and cooling. In that case it is theoretically possible to heat and cool buildings. Without the intervention of heat pumps. However, a back up systems is still favourable. In most cases however indirect heating and cooling is applicable where the final supply temperatures are post processed by heat pumps. Heat load duration curves give information about the hours in the year that this post processing is necessary.

Indirect heating and cooling is always the case if other emission systems then floor heating/cooling or concrete core activation are applied, for example low temperature enlarged radiators or low temperature forced air systems (like the new CBS office).
Table 1: Generic overview of measures to make buildings suitable for low temperature geothermal sources in comparison with current practice.

<table>
<thead>
<tr>
<th>Building Reg’s NL</th>
<th>Practice 2008 NL</th>
<th>Mine water (Lowex)</th>
</tr>
</thead>
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<tr>
<td><strong>Thermal insulation</strong></td>
<td>Envelope U = 0.37</td>
<td>Envelope U &lt; 0.25</td>
</tr>
<tr>
<td></td>
<td>Glazing U = 3.0</td>
<td>Glazing U &lt; 1.2</td>
</tr>
<tr>
<td><strong>Ventilation</strong></td>
<td>No system requirements</td>
<td>No system requirements</td>
</tr>
<tr>
<td></td>
<td>In practice 50% ME and 50% MVHR</td>
<td>MVHR with η = 95%</td>
</tr>
<tr>
<td></td>
<td>In practice 50% ME and 50% MVHR</td>
<td>MVHR with η = 95%</td>
</tr>
<tr>
<td><strong>Air tightness</strong></td>
<td>n50 = 3</td>
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</tr>
<tr>
<td></td>
<td>n50 &lt;1</td>
<td>n50 &lt;1</td>
</tr>
<tr>
<td><strong>Emission system</strong></td>
<td>No requirements</td>
<td>Radiators</td>
</tr>
<tr>
<td></td>
<td>Floor heating and cooling (residential)</td>
<td>Concrete core activation (non residential)</td>
</tr>
<tr>
<td></td>
<td>Condensing boilers</td>
<td>Condensing boilers</td>
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<tr>
<td></td>
<td>η = 95%</td>
<td>η = 95%</td>
</tr>
<tr>
<td></td>
<td>No cooling</td>
<td>No cooling</td>
</tr>
<tr>
<td><strong>HVAC system/efficiency</strong></td>
<td>No requirements (but in EPR)</td>
<td>Mine water with heat pumps (boiler back up)</td>
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<td></td>
<td>Condensing boilers</td>
<td>Sustainable cooling</td>
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<td>0.5</td>
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</tr>
</tbody>
</table>

Figure 11: Direct and indirect heating and cooling

8. EXERGY RATING BY The PER-exergy diagram

Techniques for sustainable energy or renewables are often judged by their energy savings. A more sophisticated approach is a ranking on the savings of fossil fuels (and thus reducing greenhouse gases) and the exergetic efficiency as an index for the use of low valued energy sources. Both aspects can be presented in a combined diagram as shown in figure 11.
The horizontal axis indicates for each system the so called primary energy ratio (PER). The primary energy ratio is the ratio of the useful energy output to the primary energy input i.e. the energy contained in the fossil fuel. For electrically driven heat pumps a PER can also be defined, by multiplying the COP with the power generation efficiency. The PER can be calculated for nearly every energy system or device when the conversion efficiencies are known. PER values above 1 are only possible at the energy systems which use renewables, like a solar collector. The vertical axis is het exergetic value of the system, more especially the total exergy score which is subject to the Annex 49 programme. It is calculated as:

$$\text{Exergetic efficiency} = \frac{\text{useful energy output \times quality factor}}{\text{energy input \times quality factor}}$$

Different symbols are used in the diagram for heating (red bullet), cooling (blue bullet) and DHW (light blue water drop). The size of the symbol can be used to indicate the accuracy (or spreading in the results) of the calculations. This is useful to cover up the sometimes exaggerated expectations of the accuracy of such calculations. In practice, the external influences on the actual savings like losses and suboptimal control are much bigger than the accuracy of the calculations.

In general, a high PER means that only a small part of the useful energy is extracted from fossil fuels; a high exergetic efficiency indicates a good match between the quality (temperature level) of the used and delivered energy.


Despite the rather high level of investments for the energy installations and buildings measures this concept can be economically feasible by private organized energy exploitation. In this case, the main investors will also organize the energy exploitation, i.e., in separate private owned Energy Exploitation constructions. These private organized companies can use lower internal interest rates, 6 to 8% instead of the usual 12 to 15% of utilities and district heating companies. The main reason is that profits from selling energy is not considered as a core business. By establishing connection fees for heating and cooling and avoiding a gas infrastructure on building/dwelling level, as well as avoiding extra cooling installations, these constructions offer possibilities for economical sound energy exploitation. Economical benefits will also occur because of the integrated design and especially combining heating and cooling in the same emission system (i.e. floor heating and cooling, thermally activated building components etc.). Using these combined emission systems avoids the investment.
costs for a separate cooling system. The economic value of the heat and cold out of the minewater is expressed in a GJ-price and is determined by three factors:

- the running costs of the minewater company, including electricity for the well pumps and transportation, maintenance, replacements and administration;
- the costs of the upgrading of the low valued heat and cold by the heat pumps and gas fired boilers;
- the reference energy bill of the end-user as a limit, (according to the Dutch so called NMDA-principle (= costs are not more then usual)).

The first and second costs are estimated from the load-duration curves, but can still be influenced by the positive effect of the siphon-principle between the wells (this reduces the pump energy of the wells significantly). At the other hand, the end-user will probably compare his energy bill to that of a similar dwelling with conventional heating. The calculations of the reference energy-costs are subject to many discussions and points of view, due to different interests. In basic, for the Minewater project the reference energy costs (including conventional cooling) are calculated at the level of the actual building decree. The individual consumption of cooling is not metered, but charged to a fixed rate. In this way, the metering costs are avoided, habitants start cooling as early as possible to get a maximum effect out of the limited capacity of the floor cooling and as much as possible heat is returned into the mines (heat storage). In fact, a standard or general tariff for low-exergy cooling is not yet available in the Netherlands. Essential for the economic study is the distinction between the variable and fixed costs. This ratio should be roughly equal for supplier and buyer.

The energetic and financial performance of minewater as an energy source depends on a variety of parameters. A basic calculation model which compares a minewater solution to a conventional solution at a unit level of 1 GJ is used to identify them. Important parameters are:

- direct or indirect heating and cooling by minewater (practice: mix of systems);
- effectiveness of pumping and distributing the minewater;
- type of ownership of the wells and/or the buildings;
- cost of capital for the investments;
- cost of fossil energy (natural gas versus electricity) and their future price development.

Direct heating and cooling is strongly preferred because of the high energy savings, the clear structure of costs, low investments and less dependency on fossil fuel prices. A disadvantage of direct heating and cooling with the minewater is the sensitivity for fluctuations of the minewater temperature (if any). If the minewater temperature and the buildings services temperature don’t match, post processing by heat pumps is an option. In this case, an optimization of the temperature difference ($\Delta T$) for heat extraction is necessary.

A special point of attention the is electricity use for the pumps, which are considerably high. One of the factors is the length of the grid an the fact that a certain velocity (and pressure) is necessary to avoid scaling in the pipes. The overall performance of the pumping and distribution of minewater can be improved by creating a closed loop between the wells (reduces hydrostatic pressure difference) or by a turbine in the injection well. Both techniques need more study.

It may be undesirable to have minewater in the building services and is a hydraulic separation necessary, mostly at an energy station with district heating or services to large commercial buildings. District heating schemes require a long term approach. It is therefore highly recommended to use a life cycle costing approach. Generally, smaller schemes are easier to initiate but larger schemes will deliver the better long-term savings. The cost effectiveness will depend on a range of factors including size of scheme, whether new-build or refurbishment, sectoral mix and available and applicable energy
supply alternatives (eg on or off gas grid). Special attention should be paid to the domestic hot water, which becomes dominant in low-exergy houses and can’t be provided with minewater.

Making business models and financial forecasts for minewater as a commercial energy source is of particular importance. Preferably, all activities for the use of minewater for climatisation of buildings are in one hand. In practice, the pumping and distribution can be done by a different entity than the energy consumer. This requires clear appointments between the supply and demand side of minewater. For example, the pricing of the minewater can be put in the volume consumption (m³ of minewater) or, as an alternative, in extracted energy (GJ) from the minewater. The first option allows relatively simple contracts between supplier and demander and stimulates the demander for maximum energy extraction. In the second case, the GJ-price for a half fabricate of energy should be defined at clear conditions like the temperature level and the minimum temperature difference for energy-extraction.

Furthermore, the allocation of the cost for optional extra investments like back-up systems and low-exergy climatisation system requires negotiations between the supply- and demand side of minewater energy. A basic rule for the supplier of minewater energy is that the capital costs of the investments should be roughly covered up by the fixed costs like the standing right and that the variable costs like the electricity for the pumps should be covered of by the energy price per unit sold. The supplier of minewater energy can state a fixed standing right to cover up his capital costs and a variable price (€ per GJ or m³) to cover up the pump- and distribution costs.

General recommendations are:

- a small as possible distance between the minewater source and energy demander(-s);
- matching temperatures for minewater versus building services (in general, only the latter can be influenced by low-ex emission systems);
- a clear business model and financial forecast appoints the economic and energetic return of the system.

In fact, the optimum between reducing the energy demands to allow low-ex solutions and the possibility of earning back the (extra) investments done for allowing low-ex energy sources by “selling” enough energy is fragile. Figure 12 gives an illustration:

![Figure 13: Energy demand versus profits from energy sales](image)

The case studies indicate a reduction in energy costs and CO₂-emissions of 20 to 40 % in comparison to conventional, fossil based heat and/or cold generation. The difference between the reference energy costs and the scenario’s with minewater is in fact the available financial space for the minewater production costs and possible extra investments for low-ex buildings.
10. Conclusions

Abandoned and flooded mines can be reutilized for a new sustainable energy supply for heating and cooling of buildings. The Minewater project in Heerlen shows that temperatures of ~30 °C can be found at 700 m; the temperature of the shallow wells is to be expected 16…18 °C at 250 m. These temperatures can be used for heating and cooling of buildings if these buildings are very well insulated, have energy efficient ventilation systems and have emission systems suitable to operate with moderated temperatures like floor heating or concrete core activation. Despite the rather high investment costs such projects can be economical profitable avoiding additional cooling systems and by integrated design and if energy exploitation is organised by the investors. Although the project is more or less an experiment, the project is already scaled up to extra buildings to make it commercial profitable. This requires a reliable and efficient distribution system that lasts for at least 30 years and therefore extra measures have to be taken to prevent scaling and corrosion in the piping. For the post-pilot period also extra measures will be taken, like oversized, insulated transportation pipes with leakage detection.

A important recommendation is to locate the wells and end-users as close a possible, thus avoiding necessary permits (archaeological, flora and fauna, civil infrastructure) and costs for the transport pipes. Another main recommendation is to integrate the Low-ex concept already at the first drafts of the building design and keep on convincing the building parties about the concept, of course with regard to the actual building design. A strict separation should be made between the distinct temperature levels for heating, cooling and DHW on the one hand and the seasonal influences at the other hand. Use of electricity for the transport pumps should not be neglected.

11. Acknowledgements

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Energy Transition in Parma City

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1 Introduction

This research analyses the state of the art of the energy and environmental performances of a community located in the North of Italy and defines energy systems scenarios for year 2020. Defined scenarios take into account the European targets for energy future and the recent actions and rules led by the community for improving the energy management of the built environment. Similar evaluations have been carried out in some cases, but, in this research, an innovative approach is adopted i.e. energy assessment is put beside exergy assessment.

References of this work can be considered, on one side, the wide and long-lasting debate related to the global environmental emergencies, population dynamics, energy demand trends and resources depletion and, on the other side, contributions recently developed in the framework of the IEA ECBCS Annex 49 (Low Exergy Systems for High-Performance Buildings and Communities), where the importance of considering exergy indicators (not only at building level but also at community level) beside energy ones was highlighted. Following this approach, it is essential to consider not only the quantity, but also the quality of energy used. Therefore, exergy analysis can be considered as an opportune complement to energy analysis, in order to achieve a more rational use of energy in building-related processes.

First, a set of indicators for energy and exergy evaluation has been defined, then they have been evaluated separately because they are able to represent different characteristics of an energy system and finally they have been put in common with a multi-objective approach as a set of results of a simplified steady-state tool for supporting decisions in energy planning.

Starting from the fact that the application of the exergy theory in urban sustainability practices is still lacking, this paper could represent a contribution to that end, showing in a case study that results in exergy performance indicators are not equivalent to those in the energy ones and that improving the exergy performance of a community is not an easy task. Of course, other indicators can be taken into account as it is possible to extend the investigation beyond the building sector to other relevant city flows i.e. open spaces, water cycle, transport etc.
2 Methodology

First, the energy system related to electricity, heating and cooling needs of Parma, a community of 180,000 inhabitants located in the North of Italy, has been analyzed. The state of the art of the system has been studied on the basis of recent data (i.e. year 2007) provided by the municipal utility (www.eniaspa.it). By these data, provided firstly for year 2007, a baseline scenario, called Scenario_0, has been created. As energy system evolution, other scenarios have been developed taking into account:

- Italian conditions, trends and typical targets suggested by EU for year 2020 (http://www.europeanenergyreview.eu/);
- recent rules, plans and actions concerning energy system implemented by the municipality [Manfren, 2010], [Agenzia Parma, 2010], [Butera et al., 2009]
- results from previous mentioned surveys [Caputo et al., 2009], [Caputo et al., 2009 BIS] and [Annex 49, 2009].

It has to be noted that European targets are defined considering all energy demands, transportation included, while, the boundary of our research include only electricity, heating and cooling for residential, commercial and industrial buildings included in the geographic boundary of the city of Parma.

The configuration of the energy system was divided into three sub-systems: power plants, district co-generators and building heat generators. Each sub-system can include a set of technologies (for example: PV, CHP and electric grid for the sub-system power plants; CHP with district heating for the sub-system district co-generators; solar thermal collectors, GSHPs and gas boilers for the sub-system building heat generators).

A simplified model based on an Excel tool has been implemented in order to assess:

- the set of technologies for each sub-system and relative parameters;
- heating, cooling and electricity demands for all the buildings;
- primary energy consumption for supplying requested heating, cooling and electricity;
- CO₂-equivalent emissions for supplying requested heating, cooling and electricity;
- the percentage of REs employed, defined as the avoided primary energy from non renewable sources divided by the sum of the spent and the avoided primary energy from non renewables; the percentage of REs has been calculated separately for heating, cooling and electricity and then for the whole energy system;
- the energy efficiency of: the single power plants, district cogenerators and building heat generators; the heating, cooling and electricity systems; the whole energy system, calculated as the ratio between the total energy delivered for the different uses and the total primary energy consumed;
- the exergy spent and delivered for supplying the requested demands;
- the exergy efficiency of: the single power plants, district co-generators and building heat generators; the heating, cooling and electricity systems; the whole energy system, calculated as the ratio between the total exergy delivered for the different uses and the total primary exergy spent [Caputo et al., 2009], [Angelotti et al., 2007] and [Macchi et al., 2005].
For exergy calculations, a locally and seasonally varying reference environment temperature $T_0$ was assumed, following the approach adopted in [Angelotti et al., 2007]. This temperature was set equal to the design temperature typically used to size HVAC systems (D.P.R. 1052/1977, UNI 10339/2005). Indoor temperatures were set at design conditions according to Italian standards. Therefore in winter the desired inside temperature is $T_U = 20 \, ^\circ C$ and the reference is $T_0 = -5 \, ^\circ C$; in summer $T_U = 26 \, ^\circ C$ and $T_0 = 31 \, ^\circ C$. Quality levels of the energy demands and supplies are calculated by adopting a simplified steady state exergy approach, with constant temperatures for supplies and demands [Angelotti et al., 2007] and [Favrat et al., 2008]. As results of the performed evaluations, a set of indicators has been provided in order to verify the European goals and other goals taking into account also the second law efficiency. To that end, exergy performance goals were suggested as 20% reduction of exergy spent (in relation to Scenario_0) and 5% of improvement of exergy efficiency. Moreover a 10% improvement in energy saving was proposed.

2.1 Scenario_0, year 2007

The energy system of Parma in 2007 is mainly based on fossil fuels used for electricity or for heating generation. In fact, nowadays, in the city of Parma fossil fuels are almost the unique energy source. Little PV, thermal solar and geothermal applications have been neglected. Heating demand has been assumed satisfied by gas boilers (building heat generators) and CHP and district heating (district co-generators) both coupled with radiators. Cooling demand has been assumed satisfied by air conditioners as building cooling generators (a COP equal to 3.5 has been considered). Electric demand has been assumed satisfied by the national grid (power plants; the percentage of RES related to electricity generation has been taken into account) and the CHP (district co-generators). Data regarding Scenario_0 are shown in Table 1.

Table 1: Input data for Scenario_0

<table>
<thead>
<tr>
<th>Scenario_0</th>
<th>Primary energy [MWh][Manfr en 2010]</th>
<th>RES</th>
<th>Overall energy efficiency</th>
<th>CO2 -eq, [t]</th>
<th>Spent exergy [MWh]</th>
<th>Delivered exergy [MWh]</th>
<th>Overall exergy efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating</td>
<td>1514179</td>
<td>0</td>
<td>88%</td>
<td>267395</td>
<td>1514179</td>
<td>127114</td>
<td>8,4%</td>
</tr>
<tr>
<td>Cooling</td>
<td>57940</td>
<td>14%</td>
<td>138%</td>
<td>15556</td>
<td>57940</td>
<td>1340</td>
<td>2,3%</td>
</tr>
<tr>
<td>Electricity</td>
<td>1871891</td>
<td>8%</td>
<td>40%</td>
<td>495122</td>
<td>1871891</td>
<td>749353</td>
<td>40%</td>
</tr>
<tr>
<td>Total</td>
<td>3444010</td>
<td>7,8%</td>
<td>63%</td>
<td>778036</td>
<td>3444010</td>
<td>861161</td>
<td>25,3%</td>
</tr>
</tbody>
</table>

2.2 Scenarios for year 2020 (Scenario_1, Scenario_2 and Scenario_3)

Considering the plans and regulations regarding energy future of the city of Parma, the following actions have been suggested:

- reduction of heating demand;
- reduction of the urban heat island and mitigation of summer comfort conditions, in particular by the introduction of solar control devices in buildings;
- improvement of the energy efficiency of electrical appliances and lighting;
- increasing of the heating systems efficiency, through the substitution of old standard gas boiler with new condensing boilers and, where possible, ground source heat pumps (GSHP)
implementation of REs, in particular: integration of photovoltaic systems (PV) in buildings to be refurbished, and of solar thermal (ST) for domestic hot water generation

realization of a BAT incineration plant (WtoE) with cogeneration of electricity and heating and consequent expansion of the district heating network.

On the basis of these points, the three scenarios for the improvement of the energy system of Parma for year 2020 (Scenario_1, Scenario_2 and Scenario_3) are based on the following assumptions:

- Reduction of energy demands: previous researches and simulations demonstrated that reduction of energy demands brings benefits not only in terms of primary energy and CO₂, but also in terms of exergy. For this reason, a set of very hard hypothesis, for year 2020, has been defined as follows: to maintain electric demand as in year 2007; to maintain cooling demand as in year 2007; to reduce heating demand of 20% in comparison with that of year 2007;

- Implementation of the energy strategies suggested by the energy agency of the municipality: waste to energy in cogeneration configuration and promotion of solar PV, thermal systems and GSHP for improving the efficiency of district heating network;

- Adoption of low exergy systems for heating and cooling where possible;

- Efficiency improvement assumptions of the electrical national grid (from 40% to 43%) and of building heat generator (from traditional gas boiler to condensing, progressively).
Energy Transition in Parma City

Heating supplied by systems

- Scenario_0
- Scenario_1
- Scenario_2
- Scenario_3

- electric grid + GSHP
- DHW_solar collectors
- DHW_condensing boilers
- gas CHP + district heating
- gas boilers + district heating
- waste + district heating
- condensing boilers

Cooling supplied by systems

- Scenario_0
- Scenario_1
- Scenario_2
- Scenario_3

- electric grid + ground cooling
- electric grid + air conditioning

Electricity supplied by systems

- Scenario_0
- Scenario_1
- Scenario_2
- Scenario_3

- electric grid
- gas CHP
- waste
- PV

Figure 1: Contribution of the supplied systems analyzed for Scenario_0 and 3 scenarios for year 2020
[Angelotti et al., 2010]

Scenario_1 is directly proposed by the energy agency of Parma and introduces the heating and electricity generation by WtoE. By this scenario, European goals regarding the reduction of primary energy and CO2 emissions are reached, but not the target regarding REs, as it is shown in Figure 2: therefore, this study proposes two other scenarios to get the use of 17% of REs considering all energy end-uses.

Scenario_2 includes the actions mentioned in the previous scenario and proposes the introduction of solar thermal systems for domestic hot water generation (covering just over a third of the demand on an annual basis) towards REs EU target for 2020.
Scenario 3, is really alternative and takes into account the following assumptions. CHP and district heating (district co-generators), solar collectors for DHW and GSHPs are introduced. In this case, the contribution of waste incinerator is not considered at all. Cooling demand has been assumed satisfied by air conditioners as building cooling generator and direct ground cooling. Considering the electricity, PV systems and gas CHP have been introduced.

3 Results

A comparison between these scenarios is then performed considering six different indicators (see figure 2): three of them correspond to the European targets (saving of primary energy, saving of CO₂ emissions, REs %) and the others (improvement of energy efficiency, saving of spent exergy, improvement of exergy efficiency) are introduced to consider exergy and energy efficiency of the systems.

In general, on the basis of the definition here adopted for calculating REs % and of the national average electric efficiency, the consequences of increasing REs % in electricity supply are more evident than those in cooling and heating supply. Further, scenarios able to respect REs goal at year 2020 permit also to match the other European goals.

Scenario 1 satisfies the primary energy saving and CO₂ emissions saving targets, but not the REs percentage target, because the only renewable source used is waste (waste is considered 51% as RE and 49% not, as defined by Italian law). With respect to the additional targets proposed here, it satisfies the spent exergy saving (24%) but not the energy efficiency improvement (6%) and the exergy efficiency improvement target (3%).

Scenario 2, that is obtained from Scenario 1 introducing solar thermal collectors, matches the REs percentage target of 17% (Italian REs goal for year 2020, as defined by EU in the framework of the so called EU 20-20-20 package), but still fails on the energy efficiency improvement (7%) and exergy efficiency improvement (3%). Moreover the spent exergy saving is reduced compared to Scenario 1 (22%) because solar energy is a high exergy source.

Scenario 3 matches the EU targets and, with respect to the other two scenarios, is the only one able to reach the 10% energy efficiency improvement suggested as additional target. However, the exergy targets are both unsatisfied, with a spent exergy saving equal to 2,6% and a negligible improvement in exergy efficiency. This result may be explained in terms of the significant solar energy supply (both through PVs and thermal collectors), and in terms of the adoption of a district system no more based on waste heat but on gas (fossil fuel).
4 Conclusions and discussion

This work demonstrates the importance of considering the optimization of both energy and exergy use in supporting and redirecting energy systems decisions and choices. Despite the very simple and steady state model employed, a holistic approach able to consider, in the design process, not only single buildings but the whole community is worthwhile. Starting from the fact that the application of the exergy theory in practice among the key indicators of urban sustainability is still lacking, this paper could represent a contribution to that end, showing in a case study that results in exergy performance indicators are not equivalent to those in the energy ones and that improving the exergy performance of a community is not an easy task. The suggested multi-objective approach can be useful in order to clarify the overall effects of different energy strategies and REs promotion at urban level.

Some limits of the present analysis are worth further developments. In particular, efforts are needed in order to: verify and discuss the calculation of REs% since EU suggests to consider all the energy final uses at the same way (i.e. 1 kWh renewable electricity is equal to 1 kWh renewable heat at any temperature, against any exergy principle); follow the evolution of the European targets in time and to update the mentioned goals; check the actions actually performed by the municipality of Parma and those planned to be carried out; evaluate the actual technical potentials of REs and of energy saving in Parma; connect the effects of European goals also at national level; consider also EU Emission Trading in field of CO2 reduction; include also economic evaluations; extend the investigation beyond the building sector to other relevant city flows i.e. water cycle, transport etc.
5 References


COMMUNITIES II
Conversion of military wasteland to Zero Energy City
The B&O Bad Aibling park looks to the future

Dr. Ernst Böhm
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1. The project

The B&O Bad Aibling park grounds are located in a beautiful part of southern Germany. The 70-hectare facility was built in the 1930s and originally served as a German airbase with neighboring barracks. After World War II, the site was taken over by the United States Army and converted to an intelligence base which monitored radio communications behind the Iron Curtain. Some 1,400 military personnel and their families lived and worked at the base during five decades of American use. Typical for an American base, the park-like site was largely self-sufficient. An oil-fired district heating station supplied 19.5 MW of heat to the buildings. After the end of the Cold War and the shift in eastern/western bloc borders, the base lost its importance and was almost completely abandoned by the Americans in 2004. The grounds offered an opportunity for high-quality development. The B&O real estate management and construction company took advantage of the situation and acquired the grounds in 2006.

Figure 1:
An aerial view of the grounds. At lower right is the former main access road, at upper right is the residential area, and in the green and wooded area to center right is a landscaped park; a sports park will be opened at lower centre to right, and to the left and center there will be a business complex.

(B&O Wohnungswirtschaft)

When the property was taken over from the American army, living space and usable area added up to some 72,000 square meters divided into 52 building complexes. Most residential buildings dated from the 1930s and their style of construction was clearly more German than American. Although buildings had obviously been kept in good repair, their thermal quality was poor. The district heating system for the grounds had been thoroughly modernized in the mid-1990s and was in good condition. However, the scale of heat generation was much too large. Since some buildings must be torn down and the
purpose of others is not yet clear, the plan for the government-funded model project refers only to the enclosed area indicated on the overview map below. Buildings will include residences, a hotel complex with conference facilities, food services, offices, businesses (manufacturing), a kindergarten, schools, a gymnasium and a large hall for social events. Larger residential buildings already in place will be joined by low-energy and solar passive single-family homes and duplexes, and some low-energy apartment buildings constructed of wood.

Figure 2:
Overview map of the Zero Energy City funded-project area

New buildings will be constructed in the middle section of the grounds north of the stream. Several apartment buildings will be erected, although most dwellings will be solar passive single-family homes or duplexes.¹

(Schankula Architects)

2. The project's goals

The guiding idea for the conversion project was to meet the challenge of designing a plan that could be easily replicated, and that could ultimately be a model for a Zero Energy City. Goals were to be attained by:

- applying high energy-efficiency standards and using innovative technology;
- using modern methods of project management and modern planning tools in a consistent and integral planning process;
- networking the energy generation and consumption areas of the grounds; and
- methodically monitoring the entire energy recovery system of the district.

3. Energy efficiency in buildings when the project began

Calculations made according to the standards set by the Energieeinsparverordnung (EnEV)², Germany's energy conservation ordinance, showed that a typical residential building in the project area had a primary energy demand of 459 kWh/m²/year. The situation was similar for office buildings. The gymnasium and the event hall had originally been built as airplane hangers in the 1930s and heating for their subsequent uses was makeshift. Their primary energy demand was estimated at 275 kWh/m²/year. Because the energy efficiency of all buildings was so poor, retrofitting them to meet

¹ Colors in the illustration’s key indicate where different energy efficiency standards were applied within the project.
² EnEV, the German abbreviation for this ordinance, will be used throughout this paper. The EnEV sets energy-efficiency standards for new construction and the retrofit of existing buildings.
EnEV or even better standards for new construction would mean savings in primary and supplied energy of well over 50 percent.

Figure 3: Residential and office buildings were constructed soundly, but had poor insulation and inefficient heating.

4. The plan for usage

The plan for using the site was developed from the already existing building plan which dated back to the original layout of the old military airfield in the 1930s. The project area was divided into four areas of usage. The northern section is being converted into a residential area with apartments, a conference hotel, a wellness center and vacation apartments. A Waldorf school already occupies one of the residential buildings. A landscape park will adjoin this area to the south. Some of the residential blocks in this area along the old access road have already been demolished and more will follow. Here new single-family and duplex houses will be built to meet passive house energy standards. Additionally, several four-story and seven-story buildings will be erected using innovative, largely prefabricated wooden components. A sports park will be opened at the south end. Two former airplane hangars on this site will be converted into a gymnasium and a place for public events. Next to these buildings are several large outdoor sports fields. The technology park will be located to the west.

5. Energy standards, annual load duration curves, and hydraulic analysis of the district heating grid

Energy standards for buildings in the model project are targeted to fall within the following ranges (according to the 2007 EnEV):

- New buildings’ standards will range from 50 percent of the EnEV new building standard to the standard for passive houses.
- Retrofitted buildings’ standards will range from the EnEV new building standard to nearly the standard for passive houses.

Based on the energy efficiency goals set for the 27 buildings to be serviced by the district heating grid, GEF Ingenieur AG [engineering consultants] were able to determine the annual load duration curve. It clearly shows that the base load for hot water is very low. The number of full load hours at maximum capacity is only 1,450 hours/year. An analysis of all buildings within the model project area shows a large difference in the level of needs between the north and south areas, which are separated by the Moosbach stream flowing from west to east. In the northern area, highly efficient new buildings will be constructed applying ambitious energy modernization standards. This will allow for low supply temperatures of about 55 degrees C. In the southern area of the grid, which services the model project
area as well as other buildings, annual load duration curves will be largely determined by high swings in seasonal temperatures. Supply temperatures will be at a low but conventional level between 65-75 degrees C. This has suggested dividing the grid so that each area can be serviced with its own supply temperature. This would automatically confine to the northern area alone the target of having a zero energy balance, while in the southern part an energy-efficient conversion could still be achieved.

6. Options for heating supply systems and POLIS simulations

The GEF engineering consultancy used the POLIS computer model to simulate options designed for each grid area which took B&O's interests into consideration and also matched the targets set for the model project. The following supply plans were selected:

South grid: A small biogas-fired combined heating and power unit (CHP), a peak load boiler fired by woodchips, and a large hot water storage tank to maintain supply for several days.

North grid: Solar heat feed-in to district heating grid (supply to cover 100 percent of needs in summer), decentralized heat pumps to reheat water for hot water supply and heating, and a peak load boiler fired by woodchips when solar heat runs out and the seasonal performance factor for heat pumps is poor.

The plan outlined below was adopted to reach Zero Energy City goals in the north grid. During the summer, large-scale solar facilities feed the solar heat not consumed in buildings into the heating grid. Several small decentralized storage tanks and a larger central tank cache solar heat and act as buffers, providing more efficient utilization. Each building has a self-enclosed system equipped to ensure that solar yield is used in the following order:

1) consumption comes first and overrides storage;
2) after consumption, each building's small storage tank is heated to maximum capacity;
3) surplus energy fed into the grid is supplied first to neighboring buildings; and
4) any remaining energy is then stored in the grid's central storage tank.

Buildings with solar panels primarily meet their own heating needs. If heating is not needed, the decentralized buffer tank absorbs solar energy. Once it is heated to capacity, surplus heat is conducted to the grid to supply heat to other buildings. Peaks in heat yield during hot summer months are, in a final step, transferred to a 60-m³ storage tank in the heating plant. Accordingly, grid temperature varies with the amount of solar energy available. As soon as it is insufficient for hot water generation, heat pumps integrated in the buildings reheat water in decentralized storage tanks. Low temperature differences make it likely that heat pumps will have high performance factors. If heat pump performance factors drop below 4, then a woodchip-fired boiler is activated.

A well-designed contemporary boiler house

Plans are currently underway to build a 500 kW woodchip-fueled boiler house that can be easily replicated elsewhere. It is designed to be attractive and adaptable to an urban setting as a biomass-fueled heating plant. Conceived by architect Matteo Thun, the boiler house will go up near the lower hotel parking area and connect with a large fuel storage space in the basement of Building 358.
7. **Solar thermal facilities**

Solar heat will play a major role in providing hot water and heating the buildings. There are 716 m² of flat solar panels currently in operation, and they will be joined by another 1,270 m² of mostly flat panels, some evacuated tube solar collectors, and hybrid modules (for simultaneous heat and power generation). All solar facilities are located on buildings in the residential area and therefore connected to the northern grid.

![Flat solar panels on the south-facing roof of Building 353.](image)

![Flat solar panels on the south-facing roof of Building 362.](image)

8. **Renewable energy generation with hydropower**

The Molz engineering consultancy did research on building a small hydropower plant utilizing the Moosbach stream on the grounds of the northern grid area. A weir system damming the stream had already been built in the 1950s near Building 350. Molz’s study showed that a small plant was technically feasible and would produce just under 50,000 kWh/year, with a return on capital of about five percent. B&O intends to go through with this project.

9. **Renewable energy generation with photovoltaics**

**Photovoltaic panels in open space**

The open field where antennas formerly stood west of the large halls in the conversion project area offers an ideal space for setting up photovoltaic arrays.

![PV arrays on former antenna field (B&O).](image)

- Field area in zoning plan: approx. 46,010 m²
- Module area: approx. 17,176 m²
- Peak capacity: approx. 2,425 kWp
- Annual yield (at 1080 kWh/kWp): approx. 2.6 GWh
Renewable energy generation with rooftop photovoltaic (PV) arrays

While planning photovoltaics for Halls 305, 306, and 329, calculations showed that arrays installed on these buildings could have a total usable capacity of about 433 kWp with an annual yield of some 490 MWh.

Figure 7: Overview of the hall roofs used for photovoltaics in Phase 1. (B&O)

| Module inclination: | approx. 30° |
| Module area:        | approx. 2,500 m² |
| Peak capacity:      | approx. 433 kWp |
| Annual yield (at 1080 kWh/kWp): | approx. 490 MWh |

10. Energy balances

Reflections on energy balances are restricted to the northern grid. The following conclusions can be drawn:

- If PV facilities in the south grid are not taken into consideration because they should not figure into the energy balance for the north grid, a zero energy balance cannot be achieved. The north grid, encompassing 15 buildings and their supply structure, does however have a primary energy balance that is 30 percent better than the passive house limit of 120 kWh/m²/year (the EnEV standard). This is a very good result for the project and can be attributed to the good energy-efficient standards of most buildings, the exploitation of solar thermal energy, and the woodchip-fired boiler.

- If the large-scale PV facilities in the south grid are added to the calculation, there is a clear surplus energy balance of some 290 kWh/m²/year in energy gain provided that household consumption is left out (and calculations are done using EnEV limits). If household consumption is added to the calculation, the surplus energy value still comes to about 160 kWh/m²/year.

11. Other special and innovative features of the project

The B&O Bad Aibling complex will boast other innovations to enhance the overall plan for modern and energy-efficient heating supply systems and to advance the concept of the energy-efficient city (EnEff:Stadt).

New apartment buildings will use a high degree of prefabricated wooden elements

Several four-story and seven-story buildings for mixed use will be erected north of the Moosbach stream in the middle section of the project area. The buildings’ special feature is their load-bearing wood construction, considered very innovative in Germany. These buildings will be cost-efficient with low heating needs, and even the manufacture of their elements will be environmentally friendly, consuming low amounts of energy. A high degree of prefabrication is considered an advanced feature,
especially because this promises lower building costs in the future. The first four-story building was finished at the end of April 2010, erected in just four days.

![Figure 8: Visualization of prefabricated apartment buildings constructed of wood. (Schankula)](image)

**Retrofitting – prefabricated wood elements with integrated panel heating**

The retrofitting of occupied apartment buildings generally means noise and stress for the residents. However, the amount of work to be done inside an apartment can be kept to a minimum by using innovative wooden façade elements that are mounted from the outside and have integrated insulation and new built-in windows. This method can incorporate into outside wood elements HVAC components that would otherwise be installed from inside. A special feature of this technology is the need for the very accurate measuring of irregularity in the old façade that must be incorporated into the new elements being fitted to the building. Building 353 has already been retrofitted using this technology, with panel heating mounted on the inside of some of the insulation elements.

**Rosenheim University's Solar Decathlon Home**

The Rosenheim University of Applied Sciences will assemble its Solar Decathlon Home on the B&O park grounds in the spring of 2011.

![Figure 9: Left: Solar Decathlon Home. (Rosenheim) Right: New facade on Building 353.](image)

**Retrofitting – pore ventilation façade made of natural materials**

The Deutsche Bundesstiftung Umwelt (DBU) [German environment foundation] funded two test facades with pore ventilation mounted on Building 354. Drawing fresh air in through the pores of the exterior insulation can recover heat transmission losses. The test facades in the B&O park are made almost entirely of natural materials. Fiber boards made of hemp were used as porous insulation material.
Innovative HVAC – various ventilation systems and methods for generating hot water

B&O is using the Bad Aibling model project to gain experience with a wide range of innovative building services that can be used in many other projects. In this way, B&O, the leader in a highly competitive retrofit industry, can secure further market advantages. This has synergetic effects – various ventilation systems that all meet the most up-to-date standards can be compared within the model project. Likewise, it will be possible to test a variety of innovative and energy-saving methods for heating water, whereby the hot water stations presently installed in each apartment in Building 356 are a special highlight because of their particularly energy-saving qualities.

12. Implementation of the project

Due to the size of the entire project, stakeholders went into the implementation phase before the conceptual and planning phases were completed. Retrofitting has been completed in the hotel complex and in one residential building, and is still being completed in other buildings. Some buildings have already been demolished as foreseen in Bad Aibling's zoning plan. The Solar Grid 1 system has been tested since the summer of 2009; it includes heat pumps for generating hot water in buildings.

13. Monitoring

There are plans to comprehensively monitor the energy efficiency of the entire project and make improvements wherever possible. The Rosenheim University of Applied Sciences is currently applying to take on this task in a separate EnEff:Stadt funded project. This entails installing a program package which the German Ministry of Economics and Technology has already used in several other monitoring projects. Rosenheim University will analyze the data collected and:

- manage the monitoring system while capturing data at regular intervals;
- check operational reliability with the help of plausibility controls; and
- maintain and repair the monitoring system whenever necessary.

Rosenheim’s monitoring plan has identified as many as 1,500 measuring points across the entire grounds. The plan is based on the guidelines developed by the Fraunhofer Institute for Building Physics for monitoring EnEff:Stadt projects.
14. Smart metering and consumer guidance

Another idea is to install smart metering in the vacation apartments in Building 356. When consumption values for heating and electricity are indicated for the present moment or on an hourly or daily basis, households get an easy overview of their consumption behavior and resultant costs. The financing of this technology is expected to come primarily by integrating Internet-like services.

15. Degree of innovation, ease of replication, potential for future projects

The B&O Bad Aibling project boasts a rich diversity of features that can be applied to the complex issues and scope of work faced in even larger urban areas, and in some ways it goes even beyond this. Not only has the project taken advantage of business-as-usual innovations, but B&O also took a highly important decision in using an extremely innovative heating plan that indeed possesses the quality of new high-level research. A biomass-fired boiler and a number of decentralized solar thermal facilities feed heat into an already existing district heating grid in combination with grid-fed heat pumps for generating hot water individually in buildings and with the use of central and decentralized hot water storage tanks. This allows the system to operate with low grid temperatures, making use of optimized energy efficiency measures while intensively harvesting solar energy.

Experts know that the decentralized feed-in of low heat to a local or district heating grid will play an important role in developing plans for heating in the medium and long term when fossil fuels need to be gradually replaced. It is equally clear that the Bad Aibling model project has revealed the enormous amount of research and development needed to make such large and complex grid structures a reality. Positive aspects of the B&O park are that the EnEff:Stadt model project is small enough that questions and problems can still be tackled in a purposeful way, and it sets a standard that can be readily used in other urban areas.

Partners

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Simulation and analysis of options for heating supply systems: GEF Ingenieur AG
Innovative HVAC, Solar Grid 1 test network: Enwerk, PEWO
New wood façade elements and retrofitting: Huber + Sohn
Hydropower: Molz [engineering consultancy]
Construction physics and monitoring: Rosenheim University of Applied Sciences
Energy Efficient Cities and Exergy

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1 Energy Transition on community scale

85% of the German population live in cities and agglomerations. For the first time in history this quote has risen to more than fifty percent worldwide. Private households and Trade and Services consume about forty percent of the total final energy. Cities therefore play a central role in the total energy system. But they are not only locations of dense energy consumption but also actors within the energy system who can regulate consumption patterns and optimise the energy efficiency of infrastructure by their administrative steering instruments.

The superior targets of sustainable energy supply in the scope of the goals of the German Federal Government are accepted widely and receive support from politics as well as citizens. Cities and communities take central responsibilities in the long term implementation of measures. They are the stake holders and coordinators for cities’ contribution to climate protection and the realisation of a sustainable energy supply system within their communal influence area as well as in super-regional consortia and networks.

On communal level in the past the focus was mainly laid upon the improvement of the use of the different renewable energy sources. Some communities tried to use their regulatory scope of action to make mandatory specifications on e.g. the use of solar energy on buildings or the extension of local renewable energy plants. Often the implementation is accompanied by conflicts of interest between the community, utilities and citizens’ groups because of the local implications of wind turbines or biogas plants.

These limited local approaches are characterised by the fact that they are most often engaged single actions that are usually not implemented in holistic views and development strategies of the entire energy system. To develop approaches and measure that help to accelerate and facilitate on a long-term a system change towards a visionary energy supply structure demand to open the view on the total system constellation. “Energy Efficient City” therefore contains the interaction of different components from the operational field reduction of energy consumption, development of renewable energy technologies and, during the transition period, maximum efficiency of non-renewable conversion technology.

The efficient linkage of the different demand and supply units is next to the development of storage systems and concepts the core challenge of the future transition period. For the electricity sector a number of related questions are addressed under the title „smart-grids“. But the challenges not only lie in an “intelligent” electricity supply. By mere magnitude the heat sector, energy consumed for heating buildings and for the preparation of domestic hot water, still accounts for 40% of the primary energy demand European wide. Next to reducing the energy demand by accelerated refurbishment, optimised heat and cold supply strategies offer great so far unused potentials.
1.1 Research on energy efficient community quarters

Climate protection concepts aim at the development of savings measures that promise to be efficient and cost-effective with respect to the local conditions and the specific situation. The focus lies on the analysis of the inventory of the available potentials. The decisive factor for the realisation of the foreseen targets is to bridge from potential studies to implementation. To facilitate implementation on the level of community quarters the funding of the Federal Ministry of Economics and Labor (BMWi) focuses on the support of comparably small-scale implementation projects. In contrast to concepts addressing entire communities or cities implementation can proceed quicker on quarter level. At the same time typical questions and problems of urban planning arise with the planning. A central characteristic of concepts on quarter level as well as for communities and cities are the large number of involved actors with different interests and goals steering the planning process. Typical actors next to the city planning authorities are also investors, utilities and architects and specialised planners, as well as housing companies, enterprises, owners and citizens. The complexity is therefore much higher than in a planning process of a single object. This reflects in the number of combination options between efficiency measures in the building sector and efficiency measures in the sector of energy supply and distribution as well as in the collection of data. Especially the quality of the data basis determines the quality of conclusions that are drawn from the concept evaluation. In contrary to single objects the data basis has additional areal components.

1.1.1 Potential study low-exergy supply Kassel-Oberzwehren

In June 2010 a potential study for the city of Kassel was completed analysing an exergy efficient heat supply strategy for a small housing development in an existing quarter. The goal was 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 structural concept.

The concept study aimed at:

- Optimising the CO₂-emissions caused by the heating and DHW energy demand by high energy efficiencies and the use of renewable energy sources to achieve a neutral CO₂-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 was meant to lead the way in adapting urban structures to changing climatic conditions.

Figure 1: Urban development plan Kassel-Oberzwehren.
The topic of the research project associated with this building project was the development of a potential analysis for the building site in Oberzwehren in order to achieve an energy efficient and low exergy heat supply for the new buildings. The heat supply was to be achieved by low temperature heat and to be balanced on energy and exergy basis.

The use of energy was planned to be connected to low temperature systems close to the room temperature, meaning that the supply would be very efficient, with minimal losses. Presently, usually 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 had to be adjusted to the low process temperatures.

In the project, the heat supply for the new houses was based on the use and extension of the existing infrastructure. Since the targets were set at an early stage of the project, the possibilities of setting legal requirements in the development plan were an option to be used on the buildings’ side. The amendment of the German Building Code, BauGB (2004), the German building code, had brought some new options for setting targets for CO₂-reduction at the community level. The question whether the general climate protection could be addressed by the development plan has not been legally clarified. The project in Oberzwehren was meant to provide some representative experience in this issue. The limited size, the “downtown” location of the building site (recycling of urban building sites and redensification) and the general questions addressed, made the project a good example of an initial case study.

**Approach for Kassel-Oberzwehren**

The requirements on the energetic standard of the buildings had to be set by definition in the development plan and by the contracts of sale of the premises. Further improvements concerning the energy efficiency were meant to be made during the building phase directly with the building owners, the authorities of the city of Kassel and the assigned planners and researchers. For the building site, an energetic standard had to be achieved that was significantly lower than the current legal requirements set by the energy conservation ordinance. The requirements included:

- 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 order to contribute to the discussion of upcoming climate change and possibilities of dealing with rising temperatures of extraordinary hot summer spells, the cooling of residential buildings is becoming a significant topic for the future. The cooling of residential buildings is not common in Germany today. Until now, the use of air-conditioning systems for cooling had to be avoided by recommendation of the Energy Conservation Ordinance. 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 precondition that the maximum primary energy demand is not exceeded. In
the course of the project, the possibilities for exergetic efficient cooling strategies were analysed to gain a surplus quality factor for the new buildings. The use of underground heat exchangers in connection with the large area exchange systems proved to be a promising approach.

The northern part of the building site offered the possibility of realising a heat grid optimised according to the exergy demand by avoiding primary fossil fuel use. The existing district heating pipeline supplies several buildings with large energy demands. The temperature level in the return line turned out to be high enough to supply heating energy for all the planned buildings in the northern area. The local utility showed large interest in the project, since the cooling of the overall return temperatures in the district heating grid rises the efficiency of the heating plants increasing the overall system efficiency if applied on a broader scale.

1.2 Implementation models for energy efficient cities

Cities undergo constant change. This change will accelerate in the coming decades due to massive demographic and value changes and changes in working environment, mobility and technology development. Since the scale and direction of such change can not fully be predicted, decisions on technological systems in the energy supply system have to be taken with a holistic view and maximum flexibility.

In 2008 the Federal Ministry of Education and Research (BMBF) has launched a competition on energy transition strategies of cities and communities to address these system oriented approaches. New concepts for a more efficient energy use in cities had to be developed and should be implemented in the model communities. The competition targeted at the city as legal entity of public life. Compared to the scope of the quarters approach of the BMWi the target and scale was broader and more open concerning the scale of the implementation strategies and the involved consumption sectors. The aim of this competition was to identify transferrable solutions in both technological and service approaches to enable communities to transform their energy system towards sustainability and major CO₂-reduction.

1.2.1 100% renewable energies in Wolfhagen, Germany

The city of Wolfhagen serves as a middle centre in the heart of Germany. It has approximately 14,000 inhabitants who live in the ancient city and the eleven outer city districts and villages. The city encounters the typical problems of a rural community in an economically rather weak area in central Germany. To ensure the continuous quite stable development of the past decades for the future, the city council decided to start an ambitious energy transformation process with the goal of supplying the full electrical energy demand of the city by 100% renewable local sources. To not limit the scope of energy supply to the electricity sector but to come to a holistic strategy, including all relevant energy consumption sectors, the city of Wolfhagen initiated a research and development project in cooperation with an interdisciplinary team of researchers to analyse the most efficient and promising strategy. With this approach the city of Wolfhagen successfully participated in the “energy efficient community contest” launched by the German Federal Ministry of Education and Research in 2008. The scope of the contest is to develop holistic energy transition strategies for communities. These should take into account not only technical feasibility but also implementation strategies on political level and citizen participation.

The project outline to implement the energy transition in the community was designed along a horizontal and a vertical axis. Horizontally there are three main fields of activity identified addressing the core themes of energy efficiency, smart energy production and distribution and adjusted forms of mobility. The projects and implementation measures described within these core topics are clustered according their central characteristics showing mainly implementation or research and development
emphasis. To each central field of activity a number of associated projects were allocated which are outside the project framework but show close thematic and strategic correlations with the targeted overall transition goals. As a vertical key action bridging all three core themes education and information measures have been addressed to involve and participate a broad and representative share of Wolfhagen citizens, stakeholders and decision makers acknowledging the fact that only by a broad participation within the community energy transition will be achieved.

![Figure 2: Overview of the efficiency projects towards 100% RES Wolfhagen.](image)

For Wolfhagen, next to the development of a renewable electricity supply, which shall be realised by a small community-owned wind park of five wind turbines, the main focus is on retrofitting the existing building stock and implementing and intelligent and coupled holistic energy system.

### 1.2.2 Refurbishment of the existing building stock

To reach a maximum share of renewable energies within the communal energy system the reduction of the total demand is an essential precondition. The building structure in the city of Wolfhagen is characterised by a great dominance of single-family houses used by the owners. There are only few multi-family buildings and the percentage of tenants is also under national average.

Another significant characteristic of the ownership structure is the distribution of owner age groups and building ages. A significant amount of mostly retired people still reside in single-family homes built in the 1960s and 1970s. Younger age groups can be found in either younger new built homes or in buildings dating from the 1950 and older. This indicates that there is a rather long-term stability in ownership structures in the existing housing stock.

From this situation among the distribution of in-come, chances and barriers for an increased refurbishment rate can be concluded. Most holistic refurbishment measures are taken following a change in ownership. The motivation to take extensive refurbishment measures decreases with growing age and falling household income. The fact that profound energy efficiency measures do not necessarily lead to a proportional pay-back in case of selling, refurbishments are most attractive to self-using owners with a rather long perspective of use.
All these boundary conditions lead to comparably low refurbishment rates in the community. The large number of difficult to refurbish historical building increases the effect. The project aims at tackling the barriers from three directions. A modular refurbishment concept oriented specifically towards the Wolfhagen conditions shall lower the barrier to start with measures. Small steps in adjusted and building physically proved modules shall give owners the confidence that they can achieve good results with small money without risking damage to the building structure. To give good examples for a holistic refurbishment of historical protected settings, a model project in the old city centre will be launched. The goal is to develop new public-private-partnership models to facilitate the realisation by a concerted and professional approach. The third central step-stone is a competent information and service point close to everyday life of the residents with a low contact barrier.

1.2.3 Intelligent Coupled energy supply

The national goals on energy policy foresee a rising share of renewable energies for electricity supply. By the year 2020 the share of renewables is supposed to rise to 20% mostly provided by wind but also by solar. Both are characterised by strong fluctuation in day and season which will lead to great challenges regarding grid stability and the operation of conventional power plants.

In the year 2009 local photovoltaic plants produced a total of 6 million kWh in Wolfhagen contributing more than 15% of the total energy demand. On sunny days the feed-in of the PV-plants covers more than 40% of the daily electricity demand. The city and the local utilities plan to build a communally owned wind park with a capacity of 10 MW and a yearly production of 26 million kWh. Next to questions on an efficient electricity production and the appropriate power plant infra-structure the transmission system is an often underestimated bottleneck.

The harmonisation of local production and demand is a promising strategy to pre-regulate the load durations on a local level. This means that according to the local production of electricity from fluctuating renewable sources the demand has to respond as much as possible to the supply profile. With variable tariffs the utilities develop an incentive to adapt user-behaviour to price profiles and raise the share of renewables in the grid.

Next to household appliances which are to some extent feasible buffers also electric heat pumps in buildings can serve as variable energy buffers. The building structure being a very slow reacting and tolerant energy sink can serve in combination with high efficiency electric heat pumps and storage tanks as short-term buffering elements. According to the exergy principle this would mean a non-reversible process of exergy loss but with the aim of maximum renewable energy production this can still be a very favourable concept. High exergy and storable energy carriers, even when they are renewable biomass, serve as stabilising entities to fill the gaps in the load curve.

Even though Wolfhagen is and will be in future be part of the national and European energy grid the launched projects show ways how to deal with a growing share of fluctuating supply and how to create a local benefit by stabilising load curves and energy prices.

1.2.4 Conclusion

The most sustainable change to a system will happen with a shift in paradigm. Changing the goals and aims of a system will cause it to change fundamentally. Technology developments will only contribute to this shift in paradigm if they are broadly accepted by the citizens and contribute to long-term well-being and positive development of the community. Only then energy transition will be perceived as promising adaptation to future challenges instead of just in time correction of misleading developments and limitation of damage.
Performance of Low Temperature District Heating Systems for Low Energy Houses

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Abstract

A Low Energy District Heating (LEDH) network supplying district heating water with temperature 50°C was built in Lærkehaven-Lystrup, Denmark, as a part of the ongoing “Energy Technology Development and Demonstration Programme” [EUDP, 2008] focused on “CO₂-reduction in low energy buildings and communities by implementation of low temperature district heating systems”. The network supplies 40 detached Low Energy Houses built in accordance with the requirements of the Danish low energy class 1. The project aims to test and evaluate in real conditions the concept of LEDH for the supply of low energy houses, which was previously developed and reported in the project “Development and demonstration of low-energy district heating for low energy housing” [EFP, 2007]. Two different concepts of low energy district heating substations are tested, and measurements of their performance aim to document that LEDH is a proper solution for sustainable heating systems and answer the question which concept of used substations is more favourable to be used in detached low energy houses. The preliminary results show that LEDH can provide low energy buildings with space heating and domestic hot water (DHW) with high comfort, good economy and proper cooling of district heating water, and it is a good solution for low energy buildings even in areas with decreased heat demand as detached houses settlements.

Introduction

Nowadays, building regulations have been introduced worldwide and are pushing to reduce energy consumption in buildings, because 40% of all energy consumption takes place in buildings. The energy policy of European Union is recently focused on energy savings, improving security of supply, reducing production of CO₂ and increasing the share of renewable energy [Froning, 2008]. The number of new and renovated buildings is increasing as they should meet low energy standards, and building stock is slowly transforming to be formed by low energy and nearly zero energy buildings. In Denmark, the Energy Performance of Buildings Directive [EPBD 2002/91EC] was implemented in 2006. It requires that by 2020, the energy demand for heating, cooling, DHW supply and lighting in buildings will be reduced by 75% of requirements defined by Danish Building Regulations for year 2006. Hence, a question arises, what is the best solution for supply of low energy buildings with DHW and space heating fulfilling all present and coming energy policies.
Danish energy supply is planned to be based on 100% renewable energy by 2050. For buildings, it means that the heat supply can be provided by individual heating sources (solar collectors, photovoltaic, heat pumps driven by renewable energy) or by using central heat sources and distribute heat by District Heating (DH) [Lund, 2010]. The use of individual heating solutions is expected to be the most reasonable for areas with very low heat demand caused by low density of houses, while centralised solution, i.e. DH is expected to perform better for settlements in urban areas with higher heat demand density. Nowadays, the main advantage of DH is use of cheap heat cogenerated in CHP during electricity production or in waste incineration plant, which will be otherwise lost. Another advantage of DH is the use of surplus heat from industrial processes, but exploiting these usually low temperature heat sources is not optimal in traditional high and medium temperatures DH and can be better in DH systems with lower supply temperature. The future step of the DH development is the transformation to low temperature supply. This will bring possibility to use renewable heat sources with higher efficiency than today. Moreover it fits perfectly to the concept of low exergy. Recently the energy policy is focused mainly to decrease energy consumption in buildings by better insulation of building envelopes, using heat recovery for ventilation systems or more efficient light sources. In order to step further, we need to think beyond the quantity of used energy and to take into account the quality. The quality of the energy is expressed by the concept of exergy [Schmidt, 2009]. For lighting and operation of fans of the ventilation system is needed high value exergy - electrical power, but to cover needs of space heating or DHW heating is enough to use heat with the similar exergy value, and DH is one of the possibilities how supply buildings with space heating (SH) and DHW heating with use of low exergy heat.

The study of convenience of using DH for supply of low energy houses with space heating and DHW was performed in the project “Development and Demonstration of low energy district heating for low energy buildings” [EPF, 2007]. The main obstacles for using district heating for the future were found in relatively high heat losses from the DH network and high initial costs with long payback time of investment. As the result of the project, the concept of Low Energy District Heating (LEDH) was defined. It was concluded that in case of LEDH with low supply temperature about 50°C and new concept of DH substations with continuously charged buffer tank on primary side allowing use of very small pipe diameters in the DH network, heat losses can be reduced to annual average of 12% instead of 36% in case of traditional DH concept. The results additionally show, that even in areas with low energy detached houses, LEDH is a solution economically comparable with individual heat pumps.

As the next step in development of LEDH concept, a demonstration network is built in Lystrup, Denmark to document performance of the system for 40 low energy houses. The overall LEDH philosophy and Lystrup showcase is described in the following text.

**Concept of LEDH**

Recently used traditional high and medium temperature DH systems are not optimal solution for the areas consisting of low energy buildings. It is caused by the fact, that the ratio between network heat losses and heat consumption in buildings is unacceptable high and thus cost of heat for end users will increase to pay all the heat losses and DH systems will loose competition with other solutions, e.g. individual heat pumps. The solution for future development of DH is to reduce heat losses and initial investments of DH networks. This can be done by use of new concepts of pipes e.g. twin pipes replacing traditionally used pair of pipes, use media pipes with reduced diameter, use better concepts of network design (e.g. circular network configuration) and by reducing the supply temperature of district heating water to lowest possible level [Dalla Rosa, 2010]. All mentioned measures should still guarantee high level of comfort for users for DHW heating and space heating otherwise the concept cannot be successful. Moreover use of lower supply temperature will bring exergy levels of supply and
demand side on the same level. The district heating systems designed according to this philosophy are called Low Energy District Heating Systems (LEDH).

**Supply temperature for LEDH**

We need to define how much it is possible to decrease the supply temperature and still fulfil requirements for comfort supply of DHW and SH. For low energy buildings, designed to operate with low temperature space heating systems using large surfaces or “oversized” radiators low supply temperature is not a problem and systems can reliably provide occupants with desired thermal comfort. Moreover, for very cold days occurring very rarely, the supply temperature of DH can be levelled up to cover increased heat demand as it is used in traditional DH networks. Thus the lowest possible temperature for LEDH is defined by requirements for DHW.

The requirements for DHW can be divided into two groups: hygienic and comfort. From a hygienic point of view the main problem is the bacteria Legionella. It is known that Legionella grows in DHW systems with high volume of water in the temperature range from 20°C to 46°C. The growth is stopped when the temperature of water is above 46°C, and Legionella is killed by temperatures over 55°C. In accordance with this knowledge, a widely used rule is that DHW should be heated to a temperature higher than 50°C, and in case of presence of a storage tank or recirculation in the DHW system, temperature of DHW should not fall below 55°C [EHP, 2008]. Nevertheless, the national standards are not in agreement in definition of the lowest temperature level. Due to German standard W551 [DVGW W551, 1993], DHW can be produced with a temperature lower than 50°C if the overall volume of DHW system is lower than 3 L. In such a small system, Legionella is not a problem, because it cannot propagate to such a level that it can be dangerous. To fulfil the rule of maximal volume of 3 L, the DHW system should not use storage for DHW and thus be based on instantaneous heating solution for DHW.

To satisfy DHW user’s comfort, DHW should flow from DHW tap with desired temperature in reasonable short time without temperature fluctuations. In Denmark, due to the standard DS439 [DS439, 2009], the required temperature for kitchen wash is 45°C and 40°C for shower and hand wash, and DHW with a proper temperature should be provided in 10 sec after tapping was started.

Based on facts mentioned above, DHW with temperature lower than 50°C can be provided without risk of Legionella in DHW system with overall volume lower than 3 L without use of DHW circulation. In order to satisfy requirement of 45°C hot DHW in the kitchen, the district heating water with temperature 50°C should be guaranteed on the inlet of low energy district heating substation and thus is defined lowest possible supply temperature for LEDH concept. The temperature difference of 5°C between supplied DH water and produced DHW covers the temperature drop on the DHW heat exchanger and thermal capacity of DHW pipes in the building. To fulfil also comfort requirement which aims to protect user from long waiting for DHW and thus also from wasting of water, proper temperature should be reached on tap in 10 sec after tapping started. The DHW systems built due to these requirements can be called Low Temperature DHW system.

**Low temperature DHW system**

The main challenge of a low temperature DHW system is to provide DHW from tap with desired temperature in 10 sec, without the use of DHW circulation. DHW circulation is not used because it can be very energy inefficient (its energy loss can be higher than net energy for DHW heating) and moreover the use of DHW circulation will increase minimum allowed temperature of DHW and it will have consequence in increase of minimal supply temperature of LEDH.

Since DHW circulation is not used, it is very important to decrease transportation time between heat exchanger and individual taps as much as possible. It should be done by combination of close location of tapping points to source of DHW and by use of individual feeding pipes for individual taps. Example of such design is shown in Figure 1. It is important that architects are aware of this requirement when
designing new buildings. In Table 1 are listed examples of transportation delay between heat exchanger and taps in a typical house in Lystrup. The size of feeding pipes is reduced as much as possible, but still to fulfil requirements on maximal velocity 2 m/s in order not cause noise problems and also have reasonable pressure loss. These requirements lead to typical inner pipe diameter of 10 mm. We should remember that in a DHW system without circulation, the tap delay can not be reduced on secondary side, and waiting time for DHW is defined only by length and diameter of pipe between heat exchanger and tap and by flow rate of DHW. Additionally, waiting time will be a little bit increased by thermal capacity of DHW pipes, which will in the first moment of tapping decrease temperature of delivered DHW.

Table 1: Transport delay for nominal flows for individual fixtures due to DS439, in DHW system in typical house in Lystrup, for pipes with inner diameter 10 mm

<table>
<thead>
<tr>
<th>fixture</th>
<th>nominal flow (L/min)</th>
<th>length to fixture (m)</th>
<th>volume in pipes (L)</th>
<th>velocity (m/s)</th>
<th>transport delay (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>shower</td>
<td>8.4</td>
<td>2.2</td>
<td>0.17</td>
<td>1.8</td>
<td>1.2</td>
</tr>
<tr>
<td>basin</td>
<td>3.4</td>
<td>4.1</td>
<td>0.32</td>
<td>0.7</td>
<td>5.8</td>
</tr>
<tr>
<td>kitchen</td>
<td>6.0</td>
<td>6.3</td>
<td>0.49</td>
<td>1.3</td>
<td>4.9</td>
</tr>
</tbody>
</table>

From Table 1 it can be seen, that to fulfil suggested 10 sec tap delay in typical house in Lystrup, DHW should be available on outlet of heat exchanger in short time, defined by value of 10 sec minus transport delay. The waiting time, in which the substation is able deliver DHW with desired temperature on its outlet, depends on used concept of substation and its control strategy.

For multi-storey buildings, the solution for use of LEDH is to replace central DHW and SH systems with flat substations (flat in meaning of “apartment”). In this case, each flat has its own completely separated DHW system (with volume of water below 3 L) and thus it ensures high users’ comfort and it avoids the Legionella problems sometimes experienced in big DHW systems with DHW circulation.

**LEDH substations for space heating and DHW heating**

The LEDH substations can be designed according to two different philosophies. The following text describes the substations used in Lystrup show case.

**Instantaneous Heat Exchanger Unit (IHEU)**

IHEU is classical concept of DH substation with instantaneous heat exchanger (HEX), without storage tank. (see Figure 2 – left). DHW is heated instantaneously in HEX only when tapping is performed and immediately supplied to DHW system. The substation is prototype specially developed for Lærkehaven – Lystrup project. The difference with traditionally used IHEU is in increased number of plates in heat exchanger assuring better heat transfer from primary to secondary side. It is need because temperature difference between supplied DH water on primary side and desired DHW temperature on secondary side is very small. Water volume of primary and secondary side is 1.1 L each, i.e. in relation with low temperature DHW system, limited by overall volume of 3 L, it allows for more than 20 m long distribution pipes with inner diameter 10 mm. This length is enough to distribute DHW in flats and detached houses with proper displacement of tapping points.

To fulfil comfort requirements for fast DHW supply, IHEU is equipped with external by-pass. The role of external by-pass is to keep branch pipe (connection between the pipe in the street and substation)
warm on desired temperature by recirculation of small flow back to DH return and thus keep substation in “stand-by” mode, i.e. ready to use. The higher the by-pass set-point temperature, the higher is comfort, but also payment for heat for by-pass operation. The by-pass is very important solution for periods without space heating avoiding cool down of branch pipe and securing comfortable delivery of DHW. For Lystrup showcase, by-pass set point temperature is 40°C for houses at the end of the street and 35°C for other houses. The average flow through the external by-pass for IHEU was measured to be 6 L/h [Brand, 2010], and it results in Denmark in customer overall cost about 4€ for the summer period (90 days without space heating). Another question is how much will use of by-pass increase customer’s average annual cooling (which can be fined by DH company) and how much does by-pass cost the DH provider. But anyway, by-pass should be operated at least at the end of each street, so it is better to operate by-pass in user’s substation and bring some benefit to the user.

The prototype of IHEU for Lystrup is designed with a direct connection for space heating loop, i.e. without heat exchanger, and thus DH water is circulated in radiators. The control of space heating loop in the unit takes place only by differential pressure controller, which means that temperature of water coming to the space heating loop is the same temperature as in DHN. It is not a problem to make IHEU with indirect space heating system, it depends only on tradition in individual regions, but additional heat exchanger and pump for space heating loop will increase the cost of a substation. It is also important to mention that the use of indirect space heating concept will introduce additional temperature drop on the heat exchanger, but on the other hand heat exchanger will make hydraulic separation of primary and secondary side and thus higher security in case of leak of SH system.

**Figure 2: left – Instantaneous Heat Exchanger Unit (IHEU), right –District Heating Storage Unit (DHSU)**

**District Heating Storage Unit (DHSU)**

With introduction of LEDH supplying DH water with temperature 50°C, it is no more possible to use a traditional DHW storage tank with a coil heat exchanger inside, because DHW can be heated only bellow 50°C and that means risk of Legionella. Since storing of DHW brings advantages for DH network as well as for customers, a new concept of DH substation for LEDH was developed during [EPF2007] and reported by [Paulsen, 2008]. The developed DHSU can be seen in Figure 2. The difference with a traditional DHW storage tank is the movement of water storage from secondary side to primary side to store district heating water instead of DHW. DHW is prepared only during tapping in instantaneous heat exchanger supplied by DH water mainly from the buffer tank. Based on the results from the numerical simulations and experimental measurements the optimal size of buffer tank for single family house is 115 L. The size of the buffer tank is based on the optimal cooling of DH water for charging period 12 hours. The unit has a flow limiter on primary side, which allows supply from DH network maximally 2 L/minute. The rest of the needed DH water is taken from buffer tank. Continuous small flowrate allows design network with pipes with very small diameter and assures uniform load profile of the DH network. Small pipe diameters reduce heat loss from DH network and reduce investment cost. DHSU does not need the by-pass, because at least from beginning of tapping
DH water is taken mainly from buffer tank and not from cooled supply branch pipe. The disadvantage of the unit is heat loss from the buffer tank and in some cases also worse cooling of DH water. The improper cooling happens when DH water stored in the buffer tank needs to be a little reheated because it was cooled down by heat loss from buffer tank. In this period, DH water from the bottom of the buffer tank with quite high temperature is sent back to the DH. To avoid supply of not properly cooled water back to DH, the special loop allowing supply of not properly cooled DH water to the floor heating loop was designed. In the floor heating loop heating the bathroom, water is additionally cooled and then sent back to the DH network. Finally we should mention that DHSU costs roughly 2 times more than IHEU, mainly because of needed buffer tank and circulation pump.

The DHSU is built with mixing loop and flow temperature controller for space heating system based on outdoor temperature (heating curve – variable flow temperature) and thus providing space heating loop directly with temperature needed to establish thermal comfort in the building. In Lystrup, DHSU units are installed in a separated room, and air warmed by heat loss from the unit is exhausted by a ventilation system with heat recovery.

**LEDH demonstration in Lærkehaven - Lystrup**

Full scale demonstration of LEDH concept was built in Lærkehaven, in Lystrup, Denmark [Olsen, 2009]. In the residential area “C” in Lærkehaven, 40 low energy houses, built in accordance with Danish class 1 requirements are connected to LEDH system, with designed forward temperature from heat plant 52°C. For primary side of the substation, a forward temperature of 50°C is guaranteed for all installations and return temperature is designed to 25°C.

The LEDH network is based on twin pipes. It consists of flexible twin pipes for dimensions up to DN 32 and of steel twin pipes for bigger diameters. Two types of district heating substations providing houses with DHW and space heating are tested by customers in real conditions. The first concept is 29 Instantaneous Heat Exchanger Units (IHEU), second is 11 District Heating Storage Units (DSWU). The demonstration project represents the first attempt to show the potential of the integration of energy conservation policies in the building side together with the use of a low-energy (and low-exergy) district heating system. The experience gained during the planning process and the results from the measurements on site are collected, evaluated and used for continual improvement of Lystrup LEDH systems. The knowledge will be disseminated in the framework of a Danish EUDP project [EUDP, 2008] and of IEA-ECBCS Annex 51. The final conclusion from the project will be a guideline for designing of LEDH systems for low energy houses.

**Buildings**

In Lystrup two sizes of houses are built, one with area of 110 m² and second with area 90 m². Based on the numerical simulations, expected heat demand for the buildings is 30 kWh/m² per year. The houses are one storey, built from prefabricated elements. This solution was chosen in order to assure high quality of building and low price. The houses are fully occupied from April 2010. The houses are heated by radiators with design temperature 55/25°C and floor heating is installed in the bathroom.

**Network design**

The network (layout is depicted in Figure 3) is designed due to LEDH requirements, that means with low supply/return temperature, reduced diameter of media pipes, and where is possible with flexible twin pipes. The reduced diameter of media pipes results in lower heat loss in network, but on the other hand in higher pressure drop in the pipes than for traditional network design. For this reason network design pressure is quite high, slightly below 10 bars. The relatively high pressure loss is covered by an additional pump in the network. By reduction of heat losses of the LEDH network is expected to save much more energy than is needed for pumps to cover higher pressure losses in the
network. The pump is controlled according to minimal differential pressure in substation by two critical consumers. The minimal allowable differential pressure is 0.3 bars.

The Lystrup LEDH network has not its own source of heat. 50°C DH water is supplied from neighbouring traditional medium temperature DH network, by blending of 65°C hot medium temperature supply with LEDH return in the mixing loop. The mixing loop is placed in the common house together with the pumping station. A thermostatic by-pass is placed at the end of each street and additionally an external by-pass on the substation is installed in case of IHEU units, keeping branch pipes warm.

**Dimensioning of the network**

Dimensioning of the branch pipes is different for each substation type. For IHEU is dimensioning based on maximal power 32kW needed for DHW peak consumption [DS439, 2009]. Considering the rule of maximal velocity of DH water in branch pipe 2 m/s, a branch pipe with inner diameter 15 mm is designed for IHEU. For DHSU branch pipes are dimensioned mainly based on power 2.2 and 2.6 kW needed for SH system to provide smaller or bigger houses with indoor temperature 20°C. Additional 0.5 kW is added if occupants prefer temperature 22°C instead of 20°C in their houses. Last part of the power needed to be accounted for dimensioning is power needed for charging of buffer tank for DHW production. The needed power is 0.5 kW, based on assumption that is needed to charge 115 L buffer tank with temperature difference 45°C in 12 hours. Branch pipe for DHSU has inner diameter 10 mm, and it can be even smaller if there will be such small diameter available. The design power demand is shown in Table 2.

**Table 2: Designed power demand for DH substations**

<table>
<thead>
<tr>
<th></th>
<th>District Heating Storage Unit (DHSU)</th>
<th>Instantaneous Heat Exchanger Unit (IHEU)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type C1</td>
<td>Type C2</td>
</tr>
<tr>
<td><strong>Space Heating</strong></td>
<td>2.2</td>
<td>2.6</td>
</tr>
<tr>
<td><strong>Extra Space heating</strong></td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Domestic hot water</strong></td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2.9</td>
<td>3.3</td>
</tr>
</tbody>
</table>

The simultaneity factor for DHSU is equal to 1, and it does not depend on the number of connected units, because DHSU is charged continuously. Contrary, the simultaneity factor for IHEU depends on number of consumers. There are not any simultaneity factors that have been consolidated by experience for areas with low-energy buildings, thus measurements carried out during the project will provide an improved method for designing LEDH networks in such areas.

**Measuring devices**

To document the performance of the LEDH concept in real conditions, an extensive measuring system is installed in Lystrup. The parameters listed in Table 3 are measured for each substation, both on primary and secondary side.
Additionally total flow rates and supply and return temperatures are measured for group 11 DHSU (see Figure 3, channel 204) and 11 IHEU (channel 234) installed in the same street. Finally, energy consumption of the main pump (channel 113) and forward and return temperature on the main mixing loop (channel 111) are measured as well. Since measuring systems gathering huge amounts of data, sampling time of individual meters, can be only every 4 minutes. It allows evaluate overall performance of the system and substations, but for normal operation it does not allow for fast measurements, e.g. comfort level for DHW tapping, which needs measurements with very short time step. Comfort for DHW tapping is measured individually in the laboratory.

Results from measurements in Lystrup

Since the measuring system in Lærkehaven was completely started not long time ago, we cannot present detailed results from on-site measurements, but we can see that the LEDH system is working properly and there are no complaints from customers. Unfortunately, data evaluating the performance of space heating systems of houses with forward temperature 50°C are not available yet, because during the first winter (2009/2010) some problems in network emerged and network should be operated with a higher supply temperature. Recently, the problems are solved and winter 2010/2011 will bring desired data for evaluation of performance of radiator based space heating system in low energy houses. For DHW supply, some data are already available.

Results for DHW supply

The results measured in Lystrup show that DHW is prepared by both types of substations with sufficiently high temperature, at least 47°C. What is not possible to see is dynamic behaviour of substation, i.e. how long it takes a substation to produce DHW with a desired temperature and how good is instantaneous cooling of DH water during DHW production. Waiting time for DHW is more critical for IHEU, because it is a type of substation with high dynamic behaviour than in case of DHSU, where a large amount of DH water is stored “in house”. For evaluation of users comfort, we measured dynamic behaviour of IHEU in a laboratory of Technical University of Denmark. The similar measurements for DHSU were performed in Danish Technologic Institute during year 2010 and it will be reported soon.

Results of comfort measurements of IHEU

The IHEU was measured in laboratory of Technical University of Denmark in May 2010 and work is reported in [Brand et. al., 2010]. The good substation should perform well from an energy point (proper cooling of DH water) of view, but also assure a high level of comfort for customers. The main issue related to comfort is dynamic behaviour of substation, which is crucial for supply of DHW. As was
mentioned above, the requirement is to supply DHW with a proper temperature (45/40°C for kitchen and other tapping points) within 10 sec, without temperature fluctuations [DS439, 2009]. The performed measurements took in account only performance of substation, i.e. measurements not take in consideration branch pipe and pipes for DHW supply in house.

The main objective for the measurements was to measure waiting time for DHW with temperature 42°C ($t_{w2}$) after tapping is started and cooling of DH water ($T_{12AVG}$) during production of DHW for different by-pass solutions. The substation was tested with two different controllers allowing us to investigate three by-pass solutions, i.e. no by-pass, external by-pass and internal by-pass. The measurements were performed for flow simulating showering, i.e. 8.4 L/min, with desired temperature 42°C. Nevertheless set point for DHW heating was chosen 47°C in order to have only one adjustment for all DHW tapping profiles, because DHW with temperature 45°C should be provided in the kitchen. 2°C are added to cover temperature drop in pipes (between the heat exchanger and fixtures) caused by thermal capacity of DHW distribution pipes in case that tapping was not performed for a long time. But these 2°C are only an estimation and need to be further investigated.

From Table 1 (on the page 4) can be seen, that for a typical house in Lystrup, the length between heat exchanger and shower tap is 2.2 m. It results for showering with nominal flow 8.4 L/min in transportation time 1.2 sec. It means that DHW with temperature 42°C should be on outlet of substation available latest 8.8 sec after tapping started to still have 1.2 sec to reach DHW tap and fulfil recommended 10 sec waiting time.

Table 4: Overview of time delays for all measured cases, $T_{11}$ is supply temperature of DH water, $t_{xx}$ is waiting time for DHW with desired temperature, $T_{12AVG}$ is average cooling of DH during tapping

<table>
<thead>
<tr>
<th>case number and description</th>
<th>$T_{11}$ ('C)</th>
<th>$t_{xx}$ (sec)</th>
<th>$t_{xx}$ (sec)</th>
<th>$T_{12}$ (sec)</th>
<th>$T_{12AVG}$ ('C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO BY PASS</td>
<td>50.1</td>
<td>12</td>
<td>18</td>
<td>25</td>
<td>16.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19.5</td>
</tr>
<tr>
<td>EXTERNAL BY-PASS</td>
<td>49.6</td>
<td>11</td>
<td>16</td>
<td>22</td>
<td>30.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19.3</td>
</tr>
<tr>
<td>INTRERNAL BY-PASS</td>
<td>50.8</td>
<td>8.5</td>
<td>12</td>
<td>16.5</td>
<td>42.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19.3</td>
</tr>
<tr>
<td></td>
<td>50.7</td>
<td>7</td>
<td>10</td>
<td>14</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19.1</td>
</tr>
<tr>
<td></td>
<td>50.5</td>
<td>6</td>
<td>10</td>
<td>14</td>
<td>19.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19.1</td>
</tr>
<tr>
<td></td>
<td>49.3</td>
<td>1.5</td>
<td>3.5</td>
<td>7</td>
<td>47.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>18.4</td>
</tr>
</tbody>
</table>

In Table 4 are listed waiting times for DHW supplied by IHEU for different by-pass solutions, after tapping of DHW started. We want to remind once again, that data are time delays in substation only, not considering branch pipe on primary side, nor DHW pipes in house. It can be seen that to produce DHW in time below 8.8 sec is possible only when substation is equipped with by-pass. For case 2, time delay is longer than 8.8 sec, but this is probably caused by not optimal pressure conditions for controller during the first two measurements. Detailed results can be found in [Brand et. al., 2010].

Discussion

Based on performed measurements, it is still too early to conclude which type of tested substations better for detached low energy houses, and we need to make more measurements. The data for evaluation of performance of space heating systems with supply temperature 50°C are not available yet, because during winter 2009/10, the system was running with higher temperature, but it is expected that supplied temperature (50°C) will be enough to cover heat demand of low energy houses. As a weak point of LEDH was expected comfortable delivery of DHW, mainly for IHEU. The results show that both developed concepts of DH substations are capable to produce DHW with temperature 47°C and in properly designed DHW system it is possible fulfil the requirement of 10 sec waiting time for DHW without circulation of DHW. Nevertheless, for IHEU, laboratory measurements show the importance of using by-pass to fulfil comfort requirements for DHW supply. Use of by-pass
results in little higher bill for consumed heat and decreased cooling of DH water, but it only depends whether customer prefers to pay roughly 1.5 € for the use of external by-pass in months without space heating, or prefers wait longer for DHW and flush not desirably hot DHW directly to drain, what can be even more expensive at the end of the day than use of by-pass.

Conclusion

Although there are particular small problems in the Lystrup LEDH system, they are continuously being solved and preliminary results of measurements are promising. They document that district heating with low supply temperature about 50°C is suitable for supply low energy houses with DHW with 47°C and SH in comfortable way with good economy and proper cooling of DH water. LEDH can be a good solution for SH and DHW supply for the future, even for areas with detached low energy houses and thus also for areas with higher heat demand. LEDH fits perfectly for future concept of energy supply by exploiting low exergy sources based on renewable energy and waste heat. Moreover recently used DH networks will not disappear from day to day and at one point, and all of them should be renovated and that brings big potential for the LEDH concept.

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INTEGRATION AND FUTURE PERSPECTIVES
Minimization of Costs and Environmental Impact Using Exergy-Based Methods

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Abstract

This paper discusses the integrated conventional and advanced exergetic, exergoeconomic and exergoenvironmental analyses. These analyses identify the magnitude, location and causes of thermodynamic inefficiencies, costs and environmental impacts. They also evaluate the interactions among components of the overall system and the real potential for improving a system component. The information supplied by exergy-based methods (particularly by the advanced exergy-based analyses) is very useful in understanding the operation of energy conversion systems and in developing strategies for improving them.

Keywords: Thermodynamic inefficiencies, exergy, exergoeconomics, environmental impact, exergoenvironmental analysis.

1 Introduction

The objective evaluation and the improvement of an energy conversion system from the viewpoints of thermodynamics, economics, and environmental impact require a deep understanding of

(a) the real thermodynamic inefficiencies and the processes that cause them,
(b) the costs associated with equipment and thermodynamic inefficiencies as well as the connection between these two important factors,
(c) the environmental impact associated with equipment and thermodynamic inefficiencies as well as the connection between these two sources of environmental impact,
(d) the interconnections among efficiency, investment cost and component-related environmental impact associated with the selection of specific system components, and
(e) possible measures that would improve the efficiency and the cost effectiveness and would reduce the environmental impact of the system being studied.

Energy-based methods are not suitable for answering these questions because the only thermodynamic inefficiencies identified by energy-based methods are the transfer of energy to the environment. However, the inefficiencies caused by the irreversibilities within the system being considered are, in general, by far the most important thermodynamic inefficiencies and are identifiable with the aid of an exergetic analysis.

If we want to successfully reduce thermodynamic inefficiencies, cost and environmental impacts in a system we must first understand their formation process. Exergy-based methods reveal the location,
the magnitude and the sources of inefficiencies, costs and environmental impact and allow us to study the interconnections between them.

2 Exergy-Based Methods

*Exergy-based methods* is a general term that includes the conventional and advanced exergetic, exergoeconomic, and exergoenvironmental analyses and evaluations.

The exergy concept complements and enhances an energetic analysis by calculating (a) the true thermodynamic value of an energy carrier, (b) the real thermodynamic inefficiencies in a system, and (c) variables that unambiguously characterize the performance of a system (or one of its components) from the thermodynamic viewpoint.

The real thermodynamic inefficiencies in an energy conversion system are related to exergy destruction and exergy loss. All real processes are irreversible due to effects such as chemical reaction, heat transfer through a finite temperature difference, mixing of matter at different compositions or states, unrestrained expansion, and friction. An exergy analysis identifies the system components with the highest contribution to the overall thermodynamic inefficiencies and the processes that cause them.

An exergoeconomic analysis (term proposed for the first time in [Tsatsaronis, 1984]) consists of an exergetic analysis, an economic analysis, and an exergoeconomic evaluation. Exergoeconomics is based on the *exergy costing principle*, which states that exergy is the only rational basis for assigning monetary values to energy streams and to the thermodynamic inefficiencies within the system. Mass, energy or entropy should not be used for assigning monetary values because their exclusive use results in misleading conclusions [Bejan et al., 1996; Tsatsaronis, 1999b].

According to the exergy-costing principle, the cost stream \( \dot{C}_j \) associated with an exergy stream \( \dot{E}_j \) is given by

\[
\dot{C}_j = c_j \dot{E}_j
\]  

where \( c_j \) represents the average cost per unit of exergy at which the exergy \( \dot{E}_j \) was provided to the stream being considered. Equation (1) is applied to the exergy associated with streams of matter entering or exiting a system as well as to the exergy transfers associated with the transfer of work and heat. For the cost \( C_k \) associated with the exergy \( E_k \) contained within the \( k \)-th component of a system we write

\[
C_k = c_k E_k
\]

Here \( c_k \) is the average cost per unit of stored exergy within the \( k \)-th component.

An exergoenvironmental analysis (presented for the first time in [Meyer, 2006]) consists of an exergetic analysis, a life cycle assessment (LCA) of the environmental impact and an exergoenvironmental evaluation conducted in analogy with the exergoeconomic one. The *exergoenvironmental costing principle* which is used in an exergoenvironmental analysis, states that exergy is the only rational basis for assigning environmental impact to energy streams and to the thermodynamic inefficiencies within a system [Meyer et al., 2009].
In thermodynamics, the exergy destruction represents a major inefficiency and a quantity to be minimized when the overall system efficiency should be maximized. In the design of a new energy conversion system, however, the exergy destruction within a component represents not only a thermodynamic inefficiency but, in general, also an opportunity to reduce the investment cost and sometimes also the environmental impact associated with the component being considered and, thus, with the overall system.

3 Conventional Exergy-Based Analyses

3.1 Exergetic Analysis

Using the exergy rates associated with fuel and product, $\dot{E}_{F,k}$ and $\dot{E}_{P,k}$, respectively, the exergetic balance for the $k$-th component is

$$\dot{E}_{F,k} = \dot{E}_{P,k} + \dot{E}_{D,k} \quad (3)$$

The value of the total exergy destruction within the $k$-th component ($\dot{E}_{D,k}$) can be determined through an exergy balance, or through the entropy generation within this component:

$$\dot{E}_{D,k} = \dot{m}_k \cdot T_0 \cdot s_{gen,k} \quad (4)$$

The exergetic efficiency for the $k$-th component is

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}} \quad (5)$$

3.2 Exergoeconomic Analysis

An exergoeconomic analysis is conducted at the component level of a system and identifies (a) the relative cost importance of each component, and (b) options for improving the overall cost effectiveness.

The exergoeconomic model of an energy conversion system [Bejan et al., 1996; Tsatsaronis 1999b; Lazzaretto and Tsatsaronis, 2006] consists of cost balances and auxiliary costing equations. The cost balances are written for each system component in the following form

$$\dot{C}_{P,k} = \dot{C}_{F,k} + \dot{Z}_k \quad (6a)$$

or

$$c_{P,k}\dot{E}_{P,k} = c_{F,k}\dot{E}_{F,k} + \dot{Z}_k \quad (6b)$$

Here $\dot{E}_{P,k}$ and $\dot{E}_{F,k}$ are the exergy rates associated with product and fuel, respectively, $\dot{C}_{P,k}$ and $\dot{C}_{F,k}$ are the corresponding cost rates, and $c_{P,k}$ and $c_{F,k}$ are the costs per unit of exergy for product and fuel. Finally $\dot{Z}_k$ is the sum of cost rates associated with capital investment ($CI$) and operating maintenance ($OM$) expenditures for the $k$-th component.
\[ \dot{Z}_k = \dot{Z}_k^{CI} + \dot{Z}_k^{OM} \]  

(7)

To simplify the discussion, we assume in the present paper, that the contribution of \( \dot{Z}_k^{OM} \) remains constant when the design changes, and, therefore, the changes in the value of \( \dot{Z}_k \) are associated only with changes in the capital investment cost \( \dot{Z}_k^{CI} \).

### 3.3 Exergoenvironmental Analysis

An exergoenvironmental analysis is also conducted at the component level of a system and identifies (a) the relative importance of each component with respect to environmental impact, and (b) options for reducing the environmental impact associated with the overall system. In an exergoenvironmental analysis a one-dimensional characterization indicator is obtained using a Life Cycle Assessment (LCA). This indicator is used in a similar way as the cost is used in exergoeconomics. An index (a single number) describes the overall environmental impact associated with system components and exergy carriers. The Eco-indicator 99 [Goedkoop and Spriensma, 2000] is an example of such an index and is used in this paper. It should be emphasized that the evaluation of environmental impacts will always be subjective and associated with uncertainties. However, the information extracted from the exergoenvironmental analysis is very useful. Future work should also focus on reducing the arbitrariness associated with the LCA and the index used in the analysis.

The exergoenvironmental model of an energy conversion system consists of balances and auxiliary equations associated with environmental impact.

The *environmental impact balances* are written for the \( k \)-th system component in the following form

\[ \dot{B}_{P,k} = \dot{B}_{F,k} + \dot{Y}_k \]  

or

\[ b_{P,k} \dot{E}_{P,k} = b_{F,k} \dot{E}_{F,k} + \dot{Y}_k \]  

(8b)

Here \( \dot{B}_{P,k} \) and \( \dot{B}_{F,k} \) are the environmental impact rates associated with product and fuel respectively, and \( b_{P,k} \) and \( b_{F,k} \) are the corresponding environmental impacts per unit of exergy for product and fuel.

The component-related environmental impact \( \dot{Y}_k \), which considers the entire life cycle of the \( k \)-th component, consists of the following contributions:

\[ \dot{Y}_k = \dot{Y}_k^{CO} + \dot{Y}_k^{OM} + \dot{Y}_k^{DI} \]  

(9)

Here \( \dot{Y}_k^{CO} \) is the environmental impact that is associated with construction, including manufacturing, transport and installation, \( \dot{Y}_k^{OM} \) is associated with operation and maintenance, including production of pollutants during operation, and \( \dot{Y}_k^{DI} \) refers to the environmental impact associated with disposal.

### 3.4 Iterative Improvement

The following variables may be used for improving the overall effectiveness of the \( k \)-th component in an iterative optimization [Bejan et al., 1996; Tsatsaronis 1999b]:

Exergy-Based Methods

- Exergy destruction rate, $\dot{E}_{D,k}$ (Eq. (4))
- Exergetic efficiency, $\epsilon_k$ (Eq. (5))
- Exergy destruction ratio
  \[ y_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{F,lost}} \]  
  (10)
- Cost rate associated with the exergy destruction within the $k$-th component
  \[ \dot{C}_{D,k} = c_{F,k} \dot{E}_{D,k} \]  
  (11)
- Relative cost difference
  \[ r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} = \frac{1 - \epsilon_k}{\epsilon_k} + \frac{\dot{Z}_k}{\dot{C}_{D,k}} \]  
  (12)
- Exergoeconomic factor
  \[ f_k = \frac{\dot{Z}_k^{CI}}{\dot{Z}_k^{CI} + \dot{C}_{D,k}} = \frac{\dot{Z}_k^{CI}}{\dot{Z}_k^{CI} + c_{F,k} \cdot \dot{E}_{D,k}} \]  
  (13)
- Total cost rate associated with a component, ($\dot{Z}_k + \dot{C}_{D,k}$)
- Environmental impact rate associated with the exergy destruction within the $k$-th component
  \[ \dot{B}_{D,k} = b_{F,k} \dot{E}_{D,k} \]  
  (14)
- Relative environmental impact difference
  \[ r_{b,k} = \frac{b_{P,k} - b_{F,k}}{b_{F,k}} = \frac{1 - \epsilon_k}{\epsilon_k} + \frac{\dot{Y}_k}{\dot{B}_{D,k}} \]  
  (15)
- Exergoenvironmental factor
  \[ f_{b,k} = \frac{\dot{Y}_k^{CO}}{\dot{Y}_k^{CO} + \dot{B}_{D,k}} = \frac{\dot{Y}_k^{CO}}{\dot{Y}_k^{CO} + b_{F,k} \cdot \dot{E}_{D,k}} \]  
  (16)
- Total environmental impact associated with a component, ($\dot{Y}_k + \dot{B}_{D,k}$)

The advantages and disadvantages of exergetic, exergoeconomic and exergoenvironmental analyses have been discussed elsewhere (e.g., [Bejan et al., 1996; Tsatsaronis 1999a, 1999b, 2008]. Major disadvantages of the conventional exergy-based analyses are the facts, that (a) the mutual interdependencies among the system components and (b) the real potential for improving the energy conversion system cannot be evaluated. Advanced exergy-based analyses enable these evaluations.
4 Advanced Exergy-Based Analyses

The interactions among different components of the same system can be estimated and the quality of the conclusions obtained from an exergoeconomic and exergoenvironmental evaluation can be improved, when the

- exergy destruction in each (important) system component,
- investment cost associated with such component, and
- component-related environmental impacts associated with such component, as well as the
- cost of exergy destruction within each (important) system component, and
- environmental impact of exergy destruction within such component are split into endogenous/exogenous and avoidable/unavoidable [Tsatsaronis, 2008; Tsatsaronis and Morosuk, 2008; Morosuk and Tsatsaronis, 2009].

We call the analyses based on these splittings advanced (exergetic, exergoeconomic, or exergoenvironmental) analyses.

Endogenous (exergy destruction, capital investment cost, and construction-of-component-related environmental impact) is the part of a variable within a component obtained when all other components operate ideally and the component being considered operates with the same efficiency as in the real system. The exogenous part of the variable is the difference between the value of the variable within the component in the real system and the endogenous part:

\[ \hat{E}_{D,k} = \hat{E}^{EN}_{D,k} + \hat{E}^{EX}_{D,k} \]  
\[ \hat{Z}_k = \hat{Z}^{EN}_k + \hat{Z}^{EX}_k \]  
\[ \hat{Y}_k = \hat{Y}^{EN}_k + \hat{Y}^{EX}_k \]

(17)  
(18)  
(19)

The unavoidable (\( \hat{E}^{UN}_{D,k} \)) exergy destruction cannot be further reduced due to technological limitations such as availability and cost of materials and manufacturing methods. The difference between total and unavoidable exergy destruction for a component is the avoidable exergy destruction (\( \hat{E}^{AV}_{D,k} \)) that should be considered during the improvement procedure

\[ \hat{E}_{D,k} = \hat{E}^{UN}_{D,k} + \hat{E}^{AV}_{D,k} \]

(20)

The unavoidable investment cost (\( \hat{Z}^{UN}_{D,k} \)) and construction-of-component-related environmental impact (\( \hat{Y}^{UN}_{D,k} \)) for a component can be calculated by assessing the values will always be exceeded as long as such a component is used. The avoidable investment cost and avoidable construction-of-component-related environmental impact is the difference between total value and unavoidable part of these variables, i.e.,

\[ \hat{Z}_k = \hat{Z}^{UN}_k + \hat{Z}^{AV}_k \]  
\[ \hat{Y}_k = \hat{Y}^{UN}_k + \hat{Y}^{AV}_k \]

(21)  
(22)

Combining the two splittings gives us an opportunity to calculate
the avoidable endogenous part of a variable used in an advanced exergy-based analysis \(( \hat{E}_{D,k}^{AV,EN}, \hat{Z}_{k}^{AV,EN}, \text{ or } \hat{Y}_{k}^{AV,EN} )\). This variable which can be reduced by improving the \(k\)-th component from the exergetic, economic and environmental points of view, respectively, and

the avoidable exogenous part of the same variable \(( \hat{E}_{D,k}^{AV,EX}, \hat{Z}_{k}^{AV,EX}, \text{ or } \hat{Y}_{k}^{AV,EX} )\) that can be reduced by a structural improvement of the overall system, or by improving the efficiency of the remaining components, and always of course by improving the efficiency in the \(k\)-th component.

The following variables should be used in an advanced evaluation:

- Avoidable endogenous \(( \hat{E}_{D,k}^{AV,EN} )\) and avoidable exogenous \(( \hat{E}_{D,k}^{AV,EX} )\) exergy destruction,

- Cost and environmental impact of the avoidable endogenous exergy destruction

\[
\hat{C}_{D,k}^{AV,EN} = c_{F,k} \cdot \hat{E}_{D,k}^{AV,EN}
\]

and

\[
\hat{B}_{D,k}^{AV,EN} = b_{F,k} \cdot \hat{E}_{D,k}^{AV,EN}
\]

- Avoidable endogenous \(( \hat{Z}_{k}^{AV,EN} )\) investment cost, and

- Avoidable endogenous \(( \hat{Y}_{k}^{AV,EN} )\) construction-of-component-related environmental impact.

In addition we calculate the sum of the avoidable endogenous exergy destruction within the \(k\)-th component and the avoidable exogenous exergy destructions within the remaining components caused by the \(k\)-th component

\[
\hat{E}_{D,k}^{AV,E} = \hat{E}_{D,k}^{AV,EN} + \sum_{r=1}^{n} \hat{E}_{D,r}^{AV,EX,k}
\]

Similar variables are defined for the cost rates and the environmental impact rates associated with the above sum:

\[
\hat{C}_{D,k}^{AV,E} = \hat{C}_{D,k}^{AV,EN} + \sum_{r=1}^{n} c_{F,r} \cdot \hat{C}_{D,r}^{AV,EX,k}
\]

\[
\hat{B}_{D,k}^{AV,E} = \hat{B}_{D,k}^{AV,EN} + \sum_{r=1}^{n} b_{F,r} \cdot \hat{B}_{D,r}^{AV,EX,k}
\]

The importance of the component-related costs and environmental impact is given through

\[
\hat{Z}_{k}^{AV,E} = \hat{Z}_{k}^{AV,EN} + \sum_{r=1}^{n} \hat{Z}_{r}^{AV,EX,k}
\]

\[
\hat{Y}_{k}^{AV,E} = \hat{Y}_{k}^{AV,EN} + \sum_{r=1}^{n} \hat{Y}_{r}^{AV,EX,k}
\]
Finally the overall importance of a component from the viewpoints of cost and environmental impact is given by the variables \( (\hat{C}_{D,k}^{AV,\xi} + \hat{Z}_k^{AV,\xi}) \) and \( (\hat{B}_{D,k}^{AV,\xi} + \hat{Y}_k^{AV,\xi}) \). With the aid of these variables we can also establish priorities for improving the components.

5 Example

A vapor-compression refrigeration machine with a closed compressor (Figure 1) is used as an example to demonstrate the application of the conventional and advanced exergy-based analyses [Tsatsaronis 2009]. This machine consists of a compressor with electrical motor (CM), a condenser (CD), a throttling valve (TV) and an evaporator (EV). R 134a is the primary working fluid for the refrigeration machine, whereas water is used as the secondary working fluid in the condenser and the evaporator. The product from the overall system is the cold rate \( \dot{Q}_{cold} = 50kW \), the exergy rate of which is kept constant in the analysis: \( \dot{E}_{P,lost} = \dot{E}_q - \dot{E}_s = \text{const} \). The isentropic efficiency of the compressor is assumed to be \( \eta_{CM} = 0.85 \). For simplicity, pressure drops are neglected for the primary working fluid in the condenser and evaporator.

Table 1 shows the working fluid, mass flow rate, temperature, pressure and specific physical exergy of all streams of matter shown in Figure 1. Table 2 shows the exergy rates associated with fuel, product and exergy destruction as well as the exergetic efficiency and the exergy destruction ratio for each component.

The first column of Table 3 shows the purchased equipment costs whereas the second column presents the contribution of investment costs (annual levelized carrying charges) associated with each component of the refrigeration machine. The O&M expenses were neglected in this example. For the calculation of the levelized costs, an economic life of 15 years was used for the refrigeration machine as well as a general average annual inflation rate of 2.5% and an average cost of money of 10% were applied.

Tables 3 and 4 summarize the main results from the exergoeconomic and exergoenvironmental analysis, respectively. Table 5 shows the results of the advanced exergetic analysis, whereas Tables 6 and 7 present the splitting of capital investment cost and component-related environmental impact, respectively. Finally Table 8 summarizes the results obtained from the advanced exergetic, exergoeconomic and exergoenvironmental analyses.

The results from the conventional exergetic analysis (Table 2) show that the highest exergy destruction occurs in the condenser and the evaporator. These components have also the highest avoidable endogenous exergy destruction (Table 5). The relatively low values of the variable \( f_k \) for these heat exchangers (Table 3) indicates that by increasing the surface area in these components the cost effectiveness of the overall system could be improved.

A significant part of the exergy destruction in the compressor is exogenous (Table 5) and could be reduced by improving the performance of evaporator and condenser. The throttling valve has no avoidable endogenous exergy destruction. A reduction in the exergy destruction within the throttling valve can be achieved by reducing the exergy destruction in the remaining components.

The results presented in Table 6 show that the largest part of the investment costs associated with the compressor and the evaporator can be avoided. With the exception of the compressor, the exogenous part of investment costs associated with system components can be neglected.
Exergy-Based Methods

The values shown in Tables 5 through 7 demonstrate the interactions among components with respect to thermodynamics, investment costs, and component-related environmental impact. They also show the potential for reducing inefficiencies, costs and environmental impacts. Table 8 shows that for the system analyzed here, the condenser and the evaporator are the components with the highest potential for reducing inefficiencies, costs and environmental impact of the overall system. This potential is due to the relatively high avoidable exergy destruction associated with both components. Thus by decreasing the exergy destruction in the condenser and evaporator, not only the overall thermodynamic efficiency will be improved but the product cost and the overall environmental impact will also be reduced.

6 Closure

The cost improvement of energy conversion systems requires among others appropriate trade-offs between cost of thermodynamic inefficiencies and investment costs or between the environmental impacts associated with thermodynamic inefficiencies on one side and with construction, maintenance and operation of the components on the other side. These trade-offs can be identified with the aid of exergy-based methods, which calculate the costs (and environmental impacts) of thermodynamic inefficiencies and compare them with the required investment cost (and component-related environmental impact) at the system component level. Thus, exergy-based methods identify and properly evaluate the real sources of inefficiencies, costs and environmental impacts.

From the thermodynamic viewpoint, the value of each unit of exergy destruction is the same. Exergoeconomics demonstrates that the average cost per unit of exergy destruction is different for each component and depends on the relative position of the component within the system: Components closer to the supply of exergy to the overall system have, in general, a lower cost per unit of exergy destruction than components closer to the point of supply of the product streams from the overall system. Similar conclusions apply to the environmental impact associated with exergy destruction.

![Figure 1: Vapor-compression refrigeration machine with the closed compressor.](image)
**Table 1: Thermodynamic and exergoeconomic data for the refrigeration machine shown in Figure 1.**

<table>
<thead>
<tr>
<th>Stream</th>
<th>Working fluid</th>
<th>Thermodynamic analysis</th>
<th>Exergoeconomic analysis</th>
<th>Exergoenvironmental analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$m$ [kg/s]</td>
<td>$T$ [K]</td>
<td>$p$ [bar]</td>
</tr>
<tr>
<td>1</td>
<td>R134a</td>
<td>0.3247</td>
<td>0</td>
<td>2.93</td>
</tr>
<tr>
<td>1a</td>
<td>R134a</td>
<td>0.3247</td>
<td>10</td>
<td>2.93</td>
</tr>
<tr>
<td>2</td>
<td>R134a</td>
<td>0.3247</td>
<td>49</td>
<td>8.16</td>
</tr>
<tr>
<td>3</td>
<td>R134a</td>
<td>0.3247</td>
<td>32</td>
<td>8.16</td>
</tr>
<tr>
<td>4</td>
<td>R134a</td>
<td>0.3247</td>
<td>0</td>
<td>2.93</td>
</tr>
<tr>
<td>6</td>
<td>Water</td>
<td>2.939</td>
<td>20</td>
<td>1.50</td>
</tr>
<tr>
<td>7</td>
<td>Water</td>
<td>2.939</td>
<td>25</td>
<td>1.42</td>
</tr>
<tr>
<td>8</td>
<td>Water</td>
<td>1.704</td>
<td>12</td>
<td>1.50</td>
</tr>
<tr>
<td>9</td>
<td>Water</td>
<td>1.704</td>
<td>5</td>
<td>1.42</td>
</tr>
</tbody>
</table>

**Table 2: Conventional exergetic analysis of the refrigeration machine shown in Figure 1.**

<table>
<thead>
<tr>
<th>Component</th>
<th>$\dot{E}_{r,k}$ [W]</th>
<th>$\dot{E}_{p,k}$ [W]</th>
<th>$\dot{E}_{d,k}$ [W]</th>
<th>$\varepsilon_k$ [%]</th>
<th>$\eta_k$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM</td>
<td>8 554</td>
<td>7 381</td>
<td>1 173</td>
<td>86.3</td>
<td>13.7</td>
</tr>
<tr>
<td>CD</td>
<td>2 575</td>
<td>0 496</td>
<td>2 077</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>TV</td>
<td>4 859</td>
<td>3 864</td>
<td>0 994</td>
<td>79.5</td>
<td>11.6</td>
</tr>
<tr>
<td>EV</td>
<td>3 657</td>
<td>2 031</td>
<td>1 626</td>
<td>55.5</td>
<td>19.0</td>
</tr>
</tbody>
</table>

**Table 3: Conventional exergoeconomic analysis of the refrigeration machine shown in Figure 1.**

<table>
<thead>
<tr>
<th>Component</th>
<th>$PEC_k$ [€]</th>
<th>$\dot{Z}_{k}$ [€ cent/h]</th>
<th>$\dot{C}_{D,k}$ [€ cent/h]</th>
<th>$\dot{Z}<em>{k} + \dot{C}</em>{D,k}$ [€ cent/h]</th>
<th>$c_{F,k}$ [€/GJ]</th>
<th>$c_{P,k}$ [€/GJ]</th>
<th>$r_b$ [-]</th>
<th>$f_b$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM</td>
<td>9 370</td>
<td>14.3</td>
<td>13.8</td>
<td>28.1</td>
<td>32.61</td>
<td>44.10</td>
<td>0.35</td>
<td>50.9</td>
</tr>
<tr>
<td>CD</td>
<td>1 843</td>
<td>2.8</td>
<td>33.6</td>
<td>36.4</td>
<td>45.02</td>
<td>249.10</td>
<td>4.53</td>
<td>7.71</td>
</tr>
<tr>
<td>TV</td>
<td>50</td>
<td>0.1</td>
<td>15.8</td>
<td>15.9</td>
<td>44.10</td>
<td>55.50</td>
<td>0.26</td>
<td>0.48</td>
</tr>
<tr>
<td>EV</td>
<td>1 787</td>
<td>2.7</td>
<td>32.5</td>
<td>35.2</td>
<td>55.50</td>
<td>103.70</td>
<td>0.87</td>
<td>7.74</td>
</tr>
</tbody>
</table>

**Table 4: Conventional exergoenvironmental analysis of the refrigeration machine shown in Figure 1.**

<table>
<thead>
<tr>
<th>Component</th>
<th>$Y_k$ [mPts]</th>
<th>$\dot{Y}_k$ [mPts/h]</th>
<th>$\dot{B}_{D,k}$ [mPts]</th>
<th>$\dot{Y}<em>k + \dot{B}</em>{D,k}$ [mPts/h]</th>
<th>$b_{F,k}$ [mPts/GJ]</th>
<th>$b_{P,k}$ [mPts/GJ]</th>
<th>$r_{b,k}$ [-]</th>
<th>$f_{b,k}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM</td>
<td>44.986</td>
<td>0.348</td>
<td>15.25</td>
<td>15.60</td>
<td>3 611</td>
<td>4 289</td>
<td>0.19</td>
<td>2.23</td>
</tr>
<tr>
<td>CD</td>
<td>108.382</td>
<td>0.838</td>
<td>32.72</td>
<td>33.56</td>
<td>4 377</td>
<td>23 160</td>
<td>4.29</td>
<td>2.50</td>
</tr>
<tr>
<td>TV</td>
<td>172</td>
<td>0.001</td>
<td>15.34</td>
<td>15.35</td>
<td>4 289</td>
<td>5 392</td>
<td>0.26</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>EV</td>
<td>94.320</td>
<td>0.729</td>
<td>31.56</td>
<td>32.29</td>
<td>5 392</td>
<td>9 808</td>
<td>0.82</td>
<td>2.26</td>
</tr>
</tbody>
</table>
### Table 5: Advanced exergetic analysis for the vapor-compression refrigeration machine (Figure 1).

<table>
<thead>
<tr>
<th>Component</th>
<th>$\dot{E}^{EN}_{D,k}$ [W]</th>
<th>$\dot{E}^{EX}_{D,k}$ [W]</th>
<th>$\dot{E}^{UN}_{D,k}$ [W]</th>
<th>$\dot{E}^{AV}_{D,k}$ [W]</th>
<th>$\dot{E}^{UN_EN}_{D,k}$</th>
<th>$\dot{E}^{UN_EX}_{D,k}$</th>
<th>$\dot{E}^{AV_EN}_{D,k}$</th>
<th>$\dot{E}^{AV_EX}_{D,k}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM</td>
<td>677 496</td>
<td>256 802</td>
<td>203 168</td>
<td>474 328</td>
<td>CD 85</td>
<td>TV 2</td>
<td>EV 68</td>
<td>CD 171</td>
</tr>
<tr>
<td>TV</td>
<td>24</td>
<td>1437</td>
<td>588 52</td>
<td>226 CM 50</td>
<td>TV 8</td>
<td>EV 27</td>
<td>EV 123</td>
<td>mexo 37</td>
</tr>
<tr>
<td>EV</td>
<td>1626</td>
<td>756 870</td>
<td>756 0</td>
<td>0</td>
<td>CD 0</td>
<td>CM 23</td>
<td>EV 53</td>
<td>mexo 85</td>
</tr>
</tbody>
</table>

### Table 6: Splitting the capital investment cost for components of the vapor-compression refrigeration machine.

<table>
<thead>
<tr>
<th>Component</th>
<th>$\dot{Z}^{EN}_k$ [€ cent /h]</th>
<th>$\dot{Z}^{EX}_k$ [€ cent /h]</th>
<th>$\dot{Z}^{UN}_k$ [€ cent /h]</th>
<th>$\dot{Z}^{AV}_k$ [€ cent /h]</th>
<th>$\dot{Z}^{UN_EN}_k$</th>
<th>$\dot{Z}^{UN_EX}_k$</th>
<th>$\dot{Z}^{AV_EN}_k$</th>
<th>$\dot{Z}^{AV_EX}_k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM</td>
<td>7.9 6.4</td>
<td>CD 3.3</td>
<td>4.2 10.1</td>
<td>2.3 1.9</td>
<td>CD 1.0</td>
<td>TV 0</td>
<td>EV 0.8</td>
<td>CM 2.3</td>
</tr>
<tr>
<td>CD</td>
<td>2.6 0.2</td>
<td>CM &lt;0.1</td>
<td>1.9 0.9</td>
<td>0.9 0.2</td>
<td>CM &lt;0.1</td>
<td>TV &lt;0.1</td>
<td>EV &lt;0.1</td>
<td>CM &lt;0.1</td>
</tr>
<tr>
<td>TV</td>
<td>0.1 0</td>
<td>0.1 0.1</td>
<td>0.1 0.1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>EV</td>
<td>2.7</td>
<td>0.6 2.1</td>
<td>0.6</td>
<td>2.1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 7: Splitting the capital investment cost for components of the vapor-compression refrigeration machine.

<table>
<thead>
<tr>
<th>Component</th>
<th>$\dot{Y}_{EN}^k$ [mPts/h]</th>
<th>$\dot{Y}_{EX}^k$ [mPts/h]</th>
<th>$\dot{Y}_{UN}^k$ [mPts/h]</th>
<th>$\dot{Y}_{AV}^k$ [mPts/h]</th>
<th>Splitting $\dot{Y}_{real}^k$ [mPts/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM</td>
<td>0.191</td>
<td>0.157</td>
<td>0.179</td>
<td>0.169</td>
<td>0.098</td>
</tr>
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<td></td>
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</tr>
<tr>
<td>CD</td>
<td>0.770</td>
<td>0.068</td>
<td>0.110</td>
<td>0.728</td>
<td>0.101</td>
</tr>
<tr>
<td></td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TV</td>
<td>0.001</td>
<td>0</td>
<td>0.001</td>
<td>0</td>
<td>0.001</td>
</tr>
<tr>
<td>EV</td>
<td>0.729</td>
<td>0</td>
<td>0.131</td>
<td>0.598</td>
<td>0.131</td>
</tr>
</tbody>
</table>

Table 8: Summary of the results obtained from the advanced exergy-based analyses.

<table>
<thead>
<tr>
<th>Component</th>
<th>Advanced exergetic analysis</th>
<th>Advanced exergoeconomic analysis</th>
<th>Advanced exergoenvironmental analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\dot{E}_{D,k}^{AV,\Sigma}$ [W]</td>
<td>$\dot{Z}_{k}^{AV,\Sigma}$ [cent/h]</td>
<td>$\dot{C}<em>{D,k}^{AV,\Sigma} + \dot{Z}</em>{k}^{AV,\Sigma}$ [cent/h]</td>
</tr>
<tr>
<td>CM</td>
<td>835</td>
<td>5.6</td>
<td>11.31</td>
</tr>
<tr>
<td>CD</td>
<td>1382</td>
<td>3.2</td>
<td>21.63</td>
</tr>
<tr>
<td>TV</td>
<td>20</td>
<td>0</td>
<td>1.90</td>
</tr>
<tr>
<td>EV</td>
<td>1133</td>
<td>3.9</td>
<td>21.85</td>
</tr>
</tbody>
</table>
The approaches reported here allow an integrated, consistent and detailed evaluation of an energy conversion system from the viewpoints of thermodynamics, economics and protection of the environment.

Advanced exergetic, exergoeconomic and exergoenvironmental analyses are based on a splitting of exergy destruction, cost, and environmental impact into avoidable endogenous, avoidable exogenous (with further splitting to include the effects of the remaining components), unavoidable endogenous and unavoidable exogenous values. Through these techniques we improve our understanding of energy conversion processes, of the interactions among system components as well as of the interactions among thermodynamics, economics and environmental impact.

Acknowledgement

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Bibliography


Importance of Education in Energy Transition

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Abstract. A traditional practice in sustainable built environments energy management is to analyze alternatives based on economic, legal/regulatory, administrative, technical, technological, organisational and managerial approaches. Social, cultural, ethical, psychological and educational aspects of sustainable built environments energy management receive less attention. Unfortunately, various stakeholders (owners, users, developers, financial institutions, municipalities, national authorities, architects, designers, consultants, contractors, manufacturers, users, real estate and facilities managers, etc.) often lack information and knowledge about sustainable built environments energy management due to different reasons. In order to increase the efficiency and quality of the education in energy transition, an Intelligent Library and Tutoring System (ILTS) for a IDES-EDU (Master and Post Graduate education and training in multidisciplinary teams implementing EPBD and beyond) project is under development. ILTS has the ability to personalize, maximize reuse, index, analyse and integrate valuable information and knowledge from a wide selection of existing sources.

1 Introduction

Various stakeholders (owners, users, developers, financial institutions, municipalities, national authorities, architects, designers, consultants, contractors, manufacturers, users, real estate and facilities managers, etc.) often lack information and knowledge about sustainable built environments energy management due to different reasons:

- There is a shortage of feedback from previous explicit and tacit knowledge and from new low energy houses. Too few good examples are presented.
- There is a belief that low energy houses are more expensive to build than regular new production. One reason behind such misinterpretation is the failure to assess the entire sustainable built environments energy management lifecycle.
- The information about the cases when low energy houses were evaluated and found to have a reasonable energy and indoor climate performance is minimal.
- Tenants’ associations do not always have the necessary competence. Property management is often absent.
- There is a shortage of indoor climate and energy specialists among contractors, developers and property managers.
• Users lack knowledge allowing them to assess low energy buildings (advantages of such houses—comfort, low noise, economic efficiency). As a result, low energy buildings remain unfamiliar and the demand fails to grow.

• Media fails to inform about and to stimulate interest in passive houses and does not motivate professionals and decision makers.

• Scientists have inadequate knowledge about the needs of users and contractors. It proves complicated for architects, designers and contractors to keep up with the news about new energy saving products, materials and systems.

• The education faces a fragmentation problem. All professionals (owners, users, developers, architects, designers, consultants, contractors, manufacturers, users, property and facilities managers) mostly get very narrow knowledge in their own field.

• There is a lack of financial incentives (calls for projects, subsidies, energy labels, etc.) to develop lifelong learning (web portal, seminars and workshops, technical publications presenting the codes, case studies) in the area of passive houses.

• Different stakeholders are insufficiently involved in integrated design of the building lifecycle.

• In case of passive construction, the plot ratio is not higher.

• Optimisation of building operation costs is increasingly relevant in Lithuania. People choose warmer housing and are interested in the newest solutions related to engineering systems. However, they do not have access to the essential information about that.

Also many stakeholders are not aware of the varied possibilities related to financial aid, fiscal policies (government regulation of money through taxation) and monetary policies (policies affecting the money supply, interest rates, and credit availability intended to promote sustainable built environments energy management goals). Let us consider the situation of sustainable built environments energy management in Lithuania as an example:

• No tax exemptions on land populated with passive buildings.

• No discounts on state land purchased for construction of passive buildings.

• There is no system to reward building designers and architects who design buildings with low maintenance and lifecycle costs.

• Insufficient subsidies for the development of research on the energy consumption in the buildings in question and on the most rational energy sources for such buildings.

• The VAT rates for the equipment that helps to increase energy efficiency (efficient boilers, insulation, energy meters, etc.) are too high in the domestic market. No tax credit schemes are available to ensure the owners of real estate who buy energy saving or renewable energy equipment a refund on their income tax.

• No specific loans are available giving a chance to deduce full interest or part thereof from the income tax.

• The banks do not have specific mortgage loans to finance energy saving.

What are possibilities for different stakeholders to get the required knowledge?
2 Knowledge management

In recent decades, the scenario of education in sustainable built environments energy has become more complicated, dynamic and interactive. Energy related institutions are constantly required to speed-up reflective decision-makings on time. Knowledge, therefore, is noted to be one of the most important resources contributing to sustainable built environments energy decision-making.

There is no single strategy in place to handle the sustainable built environments energy management problems that arise. One of the most effective and powerful tools for strengthening management is through systematic identification, as per the best practice of knowledge utilisation and distribution.

Knowledge has been described as information which has been used and integrated with a person’s knowledge-based experience and behavioural patterns [DeTienne 2001]. Individuals have different knowledge-based capacities and experiences, and these lead to different approaches for problem-solving and decision-making. Therefore energy related institutions must be capable of knowing how to use, manage and utilise such knowledge.

A traditional practice in sustainable built environments energy management is to analyze alternatives based on economic, legal/regulatory, administrative, technical, technological, organisational and managerial approaches. Social, cultural, ethical, psychological and educational aspects of sustainable built environments energy management receive less attention.

For example, Gabuau-Moussaoui [2009] proposes to innovate with a “new” way to analyse behaviours and to help policy makers to break the walls of “the behavioural complexity”. Gabuau-Moussaoui [2009] argue that energy efficiency, energy-using products and activities are socially embedded. More specifically, they depend on the “social age” of people (children, teenagers, young adults, parents, old age people) and on their generation (events, experiences that people did live) [Gabuau-Moussaoui 2009].

Energy related institutions can use various knowledge management strategies: experts data bases; cross project learning; active knowledge management (this knowledge management strategy is also referred to as the push strategy or codification approach); knowledge requests of experts (this knowledge management strategy is also referred to as the pull strategy or personalization approach); knowledge mapping; rewards (to motivate experts to share their knowledge); communities of practice; best practice transfer; competence management (continuous employee qualification improvement and assessment in organisations); expert-apprentice relationship; groupware technologies; knowledge databases and bookmarking engines; intellectual capital; knowledge brokers; social e-network; storytelling (transfer of tacit knowledge); after project reviews; etc. Some of these strategies (community of practice, social network, intellectual capital) are part of various knowledge management models and theories.

Energy use is nowadays a very important question, in the context of global warming and expensive prices of energy. “Energy conservation” is a paradox: environmental awareness increases, but also energy demand. Sociological knowledge concerning energy uses and energy savings remains important to understand the possible evolutions of practices and values and thus the possible future energy policies. Can the “consumer society” become a “less energy-intensive” society? [Gabuau-Moussaoui 2009].

According to Moss [2005], intermediary between different stakeholders functions include activities such as adapting technologies to contexts of application, translating knowledge into new products and services, connecting people, building networks, lobbying and advocating reform, or raising awareness and broadening perceptions.
Ornetzeder and Rorhracher [2009] analyse the development of passive houses in Austria over its first decades. The development and diffusion of passive houses by no means is merely a process of technological improvement and optimisation of construction processes, but profoundly is embedded in social and cultural contexts. Ornetzeder and Rorhracher [2009] focus on a type of actors which is crucial to organise this change process, as new actors and organisations are needed e.g. to organise integrative planning processes, to set standards and market the passive house concept, to certify components, to transfer knowledge to professionals, to assist consumers in choosing architects, installers and technologies or to organise participation processes. New interest organisations mediate between producers and the policy level, energy agencies act as system builders to transfer these new technologies and practices into the mainstream building sectors, etc. Such intermediation processes fulfilled by a broad range of organisations turn out to be of crucial importance for the coordination and shaping of the socio-technical system Ornetzeder and Rorhracher [2009].

Energy Institute Vorarlberg was responsible for the initial knowledge transfer from Germany, the dissemination of the concept in the region and it served as a platform for communication, cooperation and learning. Every new passive house project was documented and discussed at an annual summer school and similar meetings. Positive as well as negative experiences were not only disseminated within the local community but from the beginning this knowledge has also been connected to the developments in Germany. As a consequence, research on passive houses very early could build on a broader range of practical experiences and the other way round practitioners could profit from newest research findings Ornetzeder and Rorhracher [2009].

How stakeholders can learn the required knowledge?

3 Learning-by-doing, -using, searching and –interacting

The National Systems of Innovation approach concludes that important parts of the knowledge base are tacit and emerge from routine basic learning-by-doing, -using and -interacting rather than from science and technology search activities. A sociological system approach is functional and deterministic, whereas an innovation style approach refers to patterns of behaviour. To understand the style of innovation better a four-fold taxonomy of knowledge is proposed: knowledge about facts, knowledge about principles and laws of nature, the skills and capability to do something, and knowledge about who knows how to do what. The mix of these four knowledge factors will characterize the style of innovation [Lundvall 1988].

Kamp et al. [2004] research investigates how methods of learning influenced the emerging wind power industries in the Netherlands and Denmark. It is found that the manufacturing and implementation successes in Denmark contrast with the relatively poor progress in the Netherlands, and that one of the reasons for this is the contrast in learning mechanisms between the countries. Kamp et al. [2004] started from the perspective of innovation systems. Within these systems Kamp et al. [2004] place the focus on four types of learning processes: learning by searching, learning by doing, learning by using and learning by interacting. It is concluded that in Denmark, learning by interacting was the most important learning process, while in the Netherlands it was learning by searching [Kamp et al. 2004].

During learning by searching, ‘know-why’ is acquired. Learning by searching is related to the systematic and organised search for new knowledge. It is a broad concept that includes a whole spectrum of activities ranging from basic research to discovering the optimal design characteristics of a product and discovering the design characteristics desired by the market. Synonyms for learning by searching are R&D (research and development) and ‘learning by studying’ [Garud 1997].

During learning by doing, know-how is acquired. Know-how resides in individuals, organisational routines and manufacturing practices [Garud 1997].
Rosenberg [1982] writes that learning by using is especially important in connection with products that consist of complex, interdependent components. When these products are used, especially when they are subject to prolonged stress, the outcome of the interaction of the components cannot be precisely predicted by scientific knowledge or techniques. This interaction can only be assessed after intensive or prolonged use. One of the main purposes of learning by using is to determine the optimal performance characteristics of a durable product since these affect the useful life of the product [Rosenberg 1982].

Factors for success for assessing building performance in use include making sure essential features are in place; seeking simplicity, usability, manageability and responsiveness; identifying and managing downside risks; a culture of feedback with better benchmarking and constant review against client and design intentions; and more involvement of the supply side in improving and learning from the performance of buildings in use. Seven main themes are explored and initial actions suggested for the key industry players, clients and government [Bordass, Leaman and Ruyssevelt 2001].

Andersen and Lundvall [1988] introduced the concept of learning by interacting. Their main point is that successful innovation is to a large degree dependent on close and persistent user–producer contacts. The reason is that, particularly in complex innovation processes, firms are hardly ever able to have or develop all the required knowledge and skills in-house. Especially if the required information is tacit and difficult to formalise and communicate more broadly, learning has to occur during direct face-to-face contacts. The more complex the technology, the more one needs to rely on the expertise of others [Lundvall 1988; Carlsson and Stankiewicz, 1991].

Jensen et al. [2007] contrast two modes of innovation. One, the Science, Technology and Innovation (STI) mode, is based on the production and use of codified scientific and technical knowledge. The other, the Doing, Using and Interacting (DUI) mode, relies on informal processes of learning and experience-based know-how. Logit regression analysis is used to show that firms combining the two modes are more likely to innovate new products or services than those relying primarily on one mode or the other [Jensen et al. 2007].

4 Intelligent Library and Tutoring System

The Intelligent Library and Tutoring System (ILTS) consists of six subsystems: Facultative Education Packages Database, Learner Model for Theoretical Educational Packages, Tutor and Testing Model for Theoretical Educational Packages, Subsystem of Multivariant Facultative Education Package Design and Multiple Criteria Analysis, Database of Computer Learning Systems and Graphic Interface.

The Facultative Education Packages Database (FEP-DB) will be used to accumulate all information, knowledge, best practice databases and learning materials in the area of Integral Sustainable Energy Design of the Built Environment possessed by the project partners and freely available in the EU. For example, a number of IEE project have been executed on educational programmes, like Environmental Design in University Curricula and Architectural Training in Europe, and Energy Path.

The Subsystem of Multivariant Facultative Education Package Design and Multiple Criteria Analysis (SMFEPD-MCA) will have a feature for automated compilation of facultative education packages. SMFEPD-MCA, on the basis of FEP-DB, will be able to compile a rational facultative education package for each specific user. On of the main purpose for the WP5 is to develop SMFEPD-MCA that would be more flexible and more informative in selecting out and integrating rational educational material, as much by the desired area as by coverage, and that would allow the actual learner to participate and have an influence during the time of the operations by automatically designing, evaluating and selecting the educational material most suitable for him/herself. The essence of SMFEPD-MCA is selection of the most rational integrated study material from a FEP-DB. It covers the
inputting of retrieval criteria, its synonyms (further criteria) and referencing the weight of each criterion; inputting retrieval restrictions; selecting, processing and indexing information in accordance with the inputted criteria and their weights; formulating the results of the retrieval and showing them to the learner. After selecting, processing and indexing learning materials, it further covers the selecting out of composite parts (chapters/sections/paragraphs) of the learning materials under analysis and, after that, performing the multi-criteria analysis of the composite parts. This is followed by the designing of alternative variants of the selected information and performing a multi-criteria analysis of the summarised integrated alternatives of the text by which the retrieval results are then formulated. Following the selecting, processing and indexing of information, the selecting out of the composite parts of the learning materials and their further multi-criteria analysis are performed. Furthermore there is the designing of alternative variants, their analysis and the selection the most rational alternative. All this makes the ILTS more flexible and more informative since it selects out the educational material as much by the area as by the coverage. ILTS permits selecting the maximally rational information in the coverage that the learner desires. By designing alternative variants, there’s an opportunity for the learner to supplement and/or correct the already inputted criteria, modify weights, repeat search. In other words, a learner is provided an opportunity to intervene in the occurring retrieval and to redirect it so it takes into account the learner-selected priorities and the existing situation. Much data had to be processed and evaluated in carrying out the multivariant development and multiple criteria analysis of an facultative education package. Numbers of feasible alternatives can be as large as 100,000.

The Learner Model for Theoretical Educational Packages stores data that is specific to each individual learner. The Learner Model for Theoretical Educational Packages is used to accumulate information about the education of a learner, his/her study needs, training schedule, results of previous tests (if he/she has studied earlier in the Master and Post Graduate Courses for Integral Sustainable Energy Design of the Built Environment) and study results. Therefore, the Learner Model for Theoretical Educational Packages accumulates information about the whole learning history of a learner. The Learner Model for Theoretical Educational Packages starts by assessing the learner’s knowledge of the subject or what the learner already knows. Learner Model for Theoretical Educational Packages uses that data to create a representation of the learner's knowledge and his/her learning process and represents the learner's knowledge in terms of deviations from an expert's knowledge. On the basis of these deviations the system decide what composite part (chapter/section/paragraph) of the theoretical educational package should be incorporated next, and how it should be presented (text, multimedia, computer learning system, etc.).

The Database of Computer Learning Systems enables the use of the different partners institutions Web-based computer learning systems. The use of Web-based computer learning systems in solving various problems encountered in the cases in integrated building design cases will be also aimed at determining: learner's knowledge that is acquired at the university, learner's general level of education, learner's keenness of mind, learner's ability to quickly and adequately respond to changing situation.

The Tutor and Testing Model for Theoretical Educational Packages provide a model of the teaching process and supports transition to a new knowledge state. For example, information about when to test, when to present a new topic, and which topic to present is controlled by this model. The Tutor and Testing Model for Theoretical Educational Packages formulates questions of various difficulties, specifies sources for additional studies and helps to select literature and multimedia for further studies and a computer learning system to be use during studies. Traditional testing systems evaluate a learner's state by giving them a mark and do not provide a possibility to learn about one's own knowledge gaps or to improve knowledge in any other way. The Tutor and Testing Model for Theoretical Educational Packages compares the knowledge possessed by a learner (test before studies) and knowledge obtained by a learner during studies (test after studies) and then it performs a diagnosis based on the differences. By collecting information on a history of a learner's responses, the
Tutor and Testing Model for Theoretical Educational Packages provides feedback and helps to
determine strengths and weaknesses of a learner’s knowledge, and his/her new knowledge obtained
during studies is summarized and then various recommendations and offers are provided. After giving
feedback, the system reassesses and updates the learner’s skill’s model and the entire cycle is
repeated. The system provides information on testing process in a matrix and graphical form:
information on correct and incorrect answer, time distribution to every question, number of times a
learner has changed an answer to each question of a test, etc. Also the complex parameters are
presented, where not only the correctness of the answer is evaluated, but also the time required for
learner to answer as well as the doubts of selection. The received test results are saved in the results
data base. By using statistics provided by the Tutor and Testing Model for Theoretical Educational
Packages, learners can see the question’s difficulty, average the evaluation of the whole group and
learn about their position in the group before and after studies. On the basis of the aforementioned
accumulated statistical information, the The Tutor and Testing Model for Theoretical Educational
Packages points out, in an automated manner, to authors which package parts compiled by them are
less clear to learners and which should be improved.

Conclusions

In recent decades, the scenario of education in sustainable built environments energy has become
more complicated, dynamic and interactive. Energy related institutions are constantly required to
speed-up reflective decision-makings on time. Knowledge, therefore, is noted to be one of the most
important resources contributing to sustainable built environments energy decision-making. There is
no single strategy in place to handle the sustainable built environments energy management problems
that arise. One of the most effective and powerful tools for strengthening management is through
systematic identification, as per the best practice of knowledge utilisation and distribution. In order to
solve above problems, during IDES-EDU project the Intelligent Library and Tutoring System (ILTS) is
under development. ILTS is able to search and find useful material, carry out a multivariant optional
module design, multiple criteria analysis and select the most rational study material alternatives
according to individual students’ demands.

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Exergy Analysis of Building restoration
– A Case Study in Ljubljana, Slovenia

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ABSTRACT
Buildings contribute almost half of the world’s carbon dioxide (CO₂) emissions. Energy and water consumption are some of the largest and fastest growing pressures on the global environment. In buildings, the use of energy is mainly attributed to the heating and cooling. The type of material used in the building plays a significant role in the life cycle emissions of each dwelling. Changing the material use in an existing building and adding insulation could have a major impact in the energy use and the environmental impact of building in its entire life cycle. This work investigates the amount of exergy savings and the decrease in the CO₂ emissions resulting from the refurbishing of an existing building in Ljubljana. This paper has resulted from a growing awareness that in the choice of building materials, the designer must consider not only the requirements of the building owner and occupier, but also the energy savings that result, the resource base and the effects of manufacture and processing of building materials on the environment. The exergy efficiency of the material use is calculated and the environmental impact assessment of energy and material use is accounted for.

Keywords: exergy efficiency, energy consumption, building sector

INTRODUCTION
Buildings constitute one of the biggest consumers of energy and top the scale of environment polluters. The construction, the use and the demolition of buildings use large amounts of energy and produce emissions and waste that have negative impacts on the environment. After measuring and observing the consumed energy from a building, it is realized that the use phase (use and repairing) is the most onerous and corresponds to 91% of the total amounts of energy that a building uses during all its life [2]. These facts lead to the need of measuring the energy used and finding ways to minimize it. In order to achieve the minimum energy use the tool of exergy analysis can be used.

Exergy is based on the second law of thermodynamics and is defined as the maximal obtainable potential of work of a material or energy flow in relation to the environment. In an exergy analysis it can be investigated where the work potential of natural resources in relation to the surrounding environment is
lost, i.e. where the irreversibility takes places. The maximal obtainable potential of work of a flow can only be obtained completely via reversible processes. For sustainable development, the use of the exergy reservoirs of natural resources has to be minimised to a level where there is no irreversible damage to the environment and the supply of exergy to further generation is secured. [7]

Exergy analysis has been utilized in the optimization of thermal processes in power plants and in industry. However, energy systems in buildings are designed based solely on the energy conservation principle. This principle alone does not provide a full understanding of important aspects of energy use in buildings, e.g. matching the quality levels of energy supply and end-use; fully expressing the advantages of using passive (e.g. thermal insulation, window design) and ambient energy (e.g. heat pumps) in buildings. From this viewpoint, exergy analysis is an important link in understanding and designing energy flows in buildings.

DESCRIPTION OF THE BUILDING [6]

The Public Housing Fund of the Municipality of Ljubljana (Housing Fund) is maintaining about 3200 dwellings which are located in 1225 buildings. One of these buildings is situated in Steletova 8 (Figures 1, 2) and is analyzed in this project (Table 1).

Due to the high cost for energy consumed which could lead to economic problems for the Public Housing Fund (PHF), it is important to implement new methods in order to make these dwellings more economical to the inhabitants and the PHF. This action is in line with EU and Slovenian policy on sustainable development.

The implementation of certain changes could have a significant impact on the economic and environmental performance of the building. In this case material change (insulation, window frames) is implemented (Figure 3) so as to achieve better energetic behaviour of the buildings. Specifically, the changes that are made in Steletova 8 project are shown on table 2:

Figure 1: Air photograph of Steletova 8 buildings
Table 1. Steletova 8 building data

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<table>
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<tr>
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<tbody>
<tr>
<td>Heated volume</td>
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<tr>
<td>Net heating volume</td>
<td>9452 m³</td>
</tr>
<tr>
<td>Usable surface</td>
<td>3781 m³</td>
</tr>
<tr>
<td>Envelope</td>
<td>3256 m³</td>
</tr>
<tr>
<td>Geometry coefficient</td>
<td>0,28</td>
</tr>
</tbody>
</table>

Figure 2: Ground Floor Plan View of Model House

Table 2: Existing and Refurbished Construction Materials

<table>
<thead>
<tr>
<th></th>
<th>Existing constructions (W/m²K)</th>
<th>Refurbished constructions (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External Walls</td>
<td>0,57v</td>
<td>0,24</td>
</tr>
<tr>
<td>Cellar</td>
<td>0,37</td>
<td>0,19</td>
</tr>
<tr>
<td>Ground floor</td>
<td>0,52</td>
<td>0,52</td>
</tr>
<tr>
<td>Cellar ceiling</td>
<td>0,43</td>
<td>0,43</td>
</tr>
<tr>
<td>Top floor ceiling</td>
<td>0,43</td>
<td>0,17</td>
</tr>
<tr>
<td>Windows</td>
<td>2,30</td>
<td>1,10</td>
</tr>
</tbody>
</table>
Façade,Envelope:

- Facade: + 10 cm on existing 5 cm styrofoam, sum: 15 cm
- Roof: from 10 to 25 cm TI
- New windows with overall U= 1,1 W/m²K

Ventilation:

- Ventilation with 75 – 85% heat recovery

Based on the energy analysis of the building it was found that the old constructions energy use was exceeding the standards. The energy used was 76,4 kWh/m² when the limit is 56,0 kWh/m² and with the new materials this number is lowered to 5,5 kWh/m², that results in 93% less needed energy.

EXERGY ANALYSIS [3]

For the exergy analysis the “LOWEX NL” excel program was used. This is a research project output financed within the EOS LT (“Energie Onderzoek Subsidie – Langer Termijn”) programme of Senternovem. The project is carried out by the 3TU federation: Delft University of Technology, University of Twente and Eindhoven University of Technology. The project is part of the Dutch contribution to the IEA Annex 49 “Low Energy Systems for High Performance Buildings and Communities”. The project also participates in the European research C24 (COSTeXergy).

Energy and exergy flows

From a building services perspective, energy supplied to the active heating systems in a building flows from the primary energy source (e.g. a fuel) via the building services to the building envelope, and is ultimately dissipated in the outdoor environment. The spreadsheet-based tool is built in different blocks of sub-systems, each of which represents an important step in the energy flow. The tool estimates the energy demand of a building operating at steady state design conditions, based on the German National Standard (DIN 4701-10), the German Energy Conservation Regulation (EnEV) and the European Standard EN ISO 13790 (EN ISO 13790).

Input data include general information on building shell construction and building services specifications. Calculations take into consideration heat losses in the different components as well as the auxiliary
electricity required for pumps and fans. The electricity demands for artificial lighting and for driving fans in the ventilation system are also taken into consideration. On the primary energy side, the inputs are differentiated between fossil and renewable sources. On the building envelope side, average values for passive solar energy gains are estimated from standard solar radiation data, window size and glass type. Average heat losses through the building envelope are estimated based on standard design temperatures and overall heat transfer coefficients.

From a building designer’s viewpoint, a building may be regarded as a shell allowing its occupants to interact with (or shelter from) the outdoor environment. Natural resources (e.g. sunshine, wind) may supply passive heat and cold (energy) to a building, as far as the building envelope can be designed for providing the desired indoor climate conditions. Additional energy needs may be met by building services, in the form of heat and electricity.

**ANALYSIS OF RESULTS**

**Initial Construction**

The results are referred to the building with the initial construction materials that are exceeding the energy standards. The results of energy utilization for the whole process are visualized in Figures 4, 5. The diagram in Figure 4 shows results categorized by types of energy and exergy, such as heat, electricity and solar energy. The different line slopes indicate the different intensities of exergy consumption, per subsystem (primary energy, generation, storage, distribution, emission, room air, and envelope).

For the initial construction the needed amount of primary energy and exergy is 95000W, which is reduced to 55000W and 49000 respectively. The energy gains and losses are shown in figure 6. The primary energy has the biggest input, while the primary transformation has the biggest share in energy losses. In the same manner the exergy analysis curves are shown in figure 7. The primary exergy has by far the biggest share of the exergy supply while the primary exergy has the biggest share in exergy demand.

![Figure 4: Exergy and energy flows through components](image-url)
Figure 5: Exergy losses / consumption by components

Figure 6: Energy gains and losses
Refurbished Construction

The results are referred to the building after the refurbishment. The results of energy utilization for the whole process are visualized in Figures 8 and 9 and indicate the energy and exergy flow through components.

For the refurbished construction the needed amount of primary energy and exergy is 36000W, reduced from 58000W, and 33000 respectively. In the same token, the energy gains and losses are shown in figure 10, with the gains being overwhelmed by the primary energy and the losses by the primary transformation. The exergy supply and demand (figure 11) follows the same pattern.
Figure 8: Exergy and energy flows through components

Figure 9: Exergy losses / consumption by components
Exergy Analysis of building restoration

Figure 10: Energy gains and losses

Figure 11: Exergy supply and demand
CONCLUSIONS

The goal of this work was to investigate the exergy behaviour of a dwelling in Ljubljana, Slovenia, after significant intervention on its materials.

From the exergetic-energetic analysis and in Figures 4, 5, 8, 9, is noted that major losses occur in the primary energy transformation, where primary energy from a fuel is transformed into electricity, and in the heat generation involving combustion in a boiler. Figure 5 and 9 show the relative differences between exergy consumption and energy utilization. It can be seen that this difference is significantly higher during heat generation comparing to other processes.

On the other hand, for the processes during which heat enters the building at the surface of the emission system and leaves the building via its envelope, the difference between exergy consumption and energy utilization is relatively small. This is because these processes take place relatively close to environmental temperature. As a whole, this system involves relatively large exergy consumption in the boiler, for high-temperature combustion. This high-temperature heat is subsequently degraded and supplied to a heat emission system, delivering heat at a relatively low temperature, in order to keep an indoor space at a temperature rather close to the exterior temperature.

After comparing the similar diagrams for the two different cases, it occurs that the initial building consumes much more energy compared to the refurbished building and this is noted in all the transformations of energy.

Also, the demand of exergy behaves in the same way. It is observed that for the first case 60000W primary energy and 20000W solar energy are demanded, and for the second case these numbers are 40000W and 15000W.

As it was referred above, for sustainable development, the use of the exergy reservoirs of natural resources has to be minimised to a level where there is no irreversible damage to the environment, so the modifications on the building are satisfying.

REFERENCES


[3] Exergy analysis applied to building design. Poppong Sakulpipatsin, MSc, Elisa Boelman, Dr. Eng. MBA, Building Technology Section, Faculty of Architecture, Delft University of Technology.


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Annex 49 is a task-shared international research project initiated within the framework of the International Energy Agency (IEA) programme on Energy Conservation in Buildings and Community Systems (ECBCS). ECBCS Annex 49 is a three year project. 22 research institutes, universities and private companies from 12 countries are involved.

The main objective of this project is to develop concepts for reducing the exergy demand in the built environment, thus reducing the CO₂-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.

www.annex49.com

COST ACTION C24: COSTexergy

COST (European Cooperation in the field of Scientific and Technical Research) is one of the longest-running instruments supporting cooperation among scientists and researchers across Europe, allowing the coordination of nationally-funded research on a European level. COST enables scientists to collaborate in a wide spectrum of activities in research and technology. The COSTexergy project is one of the funded actions within this European programme.

The main objective of the COSTexergy project is to broadly disseminate new knowledge and practical design-support instruments that can facilitate practical application of the exergy concept to the built environment. In order to achieve this objective, the action relies on research activities carried out by its members, which focus on investigating and demonstrating how exergy analysis can be used in the development of innovative insights and concepts and support a wider deployment of low-valued heat and other renewable energy sources.

www.costexergy.eu