Energy in Buildings and Communities Programme

International Energy Agency

LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles (Annex 64)

Final Report

FRAUNHOFER VERLAG

EBC ANNEX 64 FINAL REPORT

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Communities Programme

International Energy Agency

LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles (Annex 64)

Final Report

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Executive Summary

The energy demand of the building sector for heating and cooling is responsible for more than one third of the final energy consumption in Europe and worldwide. Commonly, this energy is provided through different fossil fuel based systems. These combustion processes cause greenhouse gas (GHG) emissions and are regarded as one of the core challenges in fighting climate change and realizing the energy transition. While a lot has already been achieved, especially regarding the share of renewables in the electricity sector, there are still large potentials in the heating sector. Exploiting these potentials and synergies requires an overall analysis of the energy conversion processes within communities to achieve a holistic understanding of these processes.

The term exergy is important in this understanding because it takes account of the 'energy quality' and can help to ensure that the most appropriate source is used for a given application. For example in space heating processes natural gas, a high quality / high exergy source, is often burned to heat water to 70-80 °C which is in turn used for a low exergy application of heating rooms in a home to 20 °C. The same gas could be burned to deliver temperatures of 1,000 °C in industrial processes and the waste heat from such processes can be more appropriately used for low exergy applications as space heating.

Communities are characterised by a wide range of energy demands, for instance heating, cooling and electricity demands. Different energy quality levels (as part of exergy) are required as heat and cold flows or as electricity and fuels. On the community level, there is the possibility of supplying this energy through different sources; for instance, through roof-top photovoltaics as "high-exergy" electricity or "low-exergy" as low-temperature heat from e.g. geothermal sources or waste heat. The fluctuating electricity supply from decentralised renewable electricity production poses both opportunities and challenges for future community energy systems. The interaction between (matched) energy demand and available (fluctuating) energy sources at different quality levels (exergy factor), especially for heating and cooling supplies, has to be solved at a local level, within the community.

To identify potential savings and synergies a holistic analysis of energy flows is necessary, which allows the detection of available quality levels. The analysis has to be carried out from generation to final use in order to reduce significantly the share of primary or high-grade fossil energy used and to optimise exergy efficiency. In practical implementation, advanced technologies and innovative supply concepts must be adapted and further developed to realise the identified potentials together with the involved industry partner (system provider and consultants).

On the community scale, different types of supply systems require different supply temperatures. To obtain the maximum output from a given primary energy flow, different temperature levels can e.g. be cascaded according to the requirements of the building typology and technology. This demands an intelligent arrangement and management of the temperature levels and flows within the system. Bi-directional concepts and short term storage can be elements of a system which is not only energy efficient, but also exergy efficient. Since high-exergy resource electricity plays a special role within the evaluation processes, it is feasible, on an exergy basis, to weigh the impact of extra electricity use, for instance for pumping or ventilation, on a thermodynamically correct basis against the heat and cold applications. On this basis, a discussion on a proper and workable set of indicators will have to be held to reflect aspects of renewable and non-renewable electricity and fluctuating supply in electrical energy systems.

This collaborative project is founded on the findings of previous IEA EBC projects such as EBC Annex 37 and EBC Annex 49 which dealt mainly with the assessment of building supply. As part of the EBC Annex 64, this assessment framework has been extended for analysing community energy supply. The EBC Annex 64 focuses on both the theoretical and methodological tools as well as on modelling and on practical implementation aspects and on the evaluation of the practical application of the so-called "low- exergy approach" for community supply. A number of tools have been evaluated within the project. The resulting work contributes to technology development, the understanding of system synergies and existing implementation barriers.

The main objective is to demonstrate the advantages of the exergy analysis and the potential of low exergy thinking on a community level as energy and cost efficient solutions, in achieving 100 % renewable and

GHG emission-free energy systems. The purpose is to show a means of realising a CO_2 neutral heating and cooling energy supply on a community scale. The intention is to reach these goals by providing and collecting suitable assessment methods and planning approaches. Furthermore, the Annex provides guidelines, recommendations, a set of best-practice examples and a large amount of background material, which can be accessed via the project homepage (www.annex64.org).

The material and the results obtained are intended primarily to address the 3 following target groups:

- The energy supply and technology industry will find development ideas for future products, business models and services in the field of dynamic energy supply systems. With the breaking down of traditional centralised top-down solutions in energy supply, new fields of business can be created in combination with overall system improvement.
- Project developer and housing companies as potential customers from the above mentioned industries will benefit from innovative and more efficient technologies, as well as from improved business concepts.
- Communities will profit from the improved and more differentiated understanding of their local potentials and supply options. Communities are supported in regaining strategic competence in long-term development issues in the energy sector.

To make it easier for the target groups to access the information and material a cooperation is established with the IEA cooperation platform on District Heating and Cooling (DHC) (www.iea-dhc.org) and with the LowEx researcher's network LowEx Net (www.lowex.net).

The following main recommendations can be derived from the findings of the EBC Annex 64:

Exergy analysis as a thermodynamic concept is a method for the evaluation and improvement of energy systems in communities by reducing destruction and losses. Exergy is a central indication for the optimisation of heat and cold based processes on a community level. For that reason exergy should be established as a standard optimization indicator for energy systems, since it indicates how well the working potential of resources is being used. The term exergy is used here to provide a common objective analysis the costs of destructions and losses, and provide more insight into the cost of avoidable and unavoidable exergy destructions. But in real systems, the final aim is rarely to use the maximum potential of our resources. Other criteria are usually more important such as costs, emissions, environmental impacts etc. Exergy can be linked to these, but is not inherently connected. The connection to other objectives, such as primary energy or emissions, should be made through the exergy optimisation steps and weighting factors.

The Annex outcome delivers tailored models and approaches for different system configurations as well as boundary conditions on a community scale. Conducted case study applications prove liability of exergy models and their outcome.

In any case, the application of a simplified "Exergy thinking" approach for planning and development projects should be always considered:

- Matching the energy quality levels of demand and supply
- Clustering of energy demand exergy wise
- Identification of the local renewable energy and waste heat utilisation potentials according to the above mentioned clusters.
- Optimisation of all energy conversion processes to achieve maximum efficiency.

Based on the results obtained, it was highlighted that the exergetic assessment promotes the planning process through the "LowEx" Thinking approach. This approach contributes significantly to a more efficient energy supply at the communal level by a reduced consumption of fossil fuels and an increased share of renewable energies on a long term horizon.

Abbreviations

Abbreviations	Meaning
4GDH	4th Generation District Heating
BEX	Building EXergy Model
BTES	Borehole Thermal Energy Storage
CHP	Combined heat and power
COP	Coefficient of performance
DEA	Dynamic Exergy Analysis
DEH	District Electrical Heating
DH	District Heating
DHW	Domestic Hot Water
EBC	Technology Cooperation Programme on Energy in Buildings and Communities
ExCo	Executive Committee
GHG	Greenhouse gas
GSHP	Ground Source Heat Pump
HHV	Higher heating value
HP	Heat Pump
HT	High Temperature
HTC	High Temperature Cooling
HTC	High Temperature Consumer
HVAC	Heating ventilation and air-conditioning
IEA	International Energy Agency
IEE	Fraunhofer Institute for Energy Economics and Energy System Technology
LHV	Lower heating value
LowEx	Low Exergy
LT	Low Temperature

Abbreviations	Meaning
LTC	Low Temperature Consumer
LTDH	Low Temperature District Heating
LTH	Low Temperature Heating
MODEO	Multi-Objective District Energy System Optimization
nZEB	Net Zero Energy Building
NZEXD	Net Zero Exergy Districts
OECD	Organisation for Economic Co-operation and Development
OLEC	Optimization of Low-temperature Cluster Grids in Districts
PTES	Pit Thermal Energy Storage
PV	Photovoltaics
PVT	Photovoltaic Thermal Collector
R&D	Research and Development
REMM	Rational Exergy Management Model
SDH	Solar District Heating
SoS	System of Systems
STES	Seasonal Thermal Energy Storage
TES	Thermal Energy Storage
TTES	Tank Thermal Energy Storage
TU	Technical University
ULTDH	Ultra-low Temperature District Heating
ZEB	Zero Energy building

Definitions

Term	Definition
Allocation	Allocation is the distribution of (production-) factors from an economic view. It is used to attribute/assign primary energy expenditure, production costs or emissions of cogeneration units to the coproducts electricity and heat.
Anergy	Anergy is energy which cannot be converted into any other type of energy in a predefined environment. It therefore represents the portion of energy that has no working potential.
Higher heating value (HHV)	Simplified, the HHV represents the energy released during complete combustion when water vapour that is formed in the process completely condensates. As this value includes the working potential of the water vapour, it is relevant for an exergetic analysis.
Energy	Energy is a fundamental physical quantity that is given in the unit J (=Ws) or, derived from this, in kWh, MWh, GWh, etc. According to the first law of thermodynamics energy can neither be consumed nor created but can only be converted.
Final energy	Final energy only includes energy sources that serve the generation and conversion of useful energy respectively. Within this project the final energy is defined as the energy that reaches the consumer and which is usually accounted in the invoice.
Energy services	Energy services are the satisfied requirements and produced goods respectively which result from the use of net energy, such as illumination of areas and rooms, movement and transport as well as heating and cooling of materials and goods, physical and chemical material conversion, reshaping and many more.
Exergy	Exergy is energy that can be converted into every other form of energy, especially work, in a particular thermodynamic environment. It can therefore be referred to as the working potential of energy. The proportion of exergy of an energy is a quality characteristic of energy. Electrical and mechanical energy consist of 100 % exergy and therefore have a high quality. In contrast, thermal energy can consist of varying proportions of exergy. Depending on the thermodynamic environmental conditions, energy can be split into two parts due to the second law of thermodynamics: exergy and anergy.
Lower heating value (LHV)	Simplified, the LHV represents the energy released during complete combustion when the water vapour that is formed remains in gaseous form and does not condensate. Classical energy balances usually refer to this value, with the exception of natural gas. In this case, the energy balance refers to the HHV.
Net energy	Net energy covers all technical forms of energy that the consumer requires, such as heat, mechanical energy, light, electrical and magnetic field energy and electromagnetic radiation, to fulfil energy services. Net energy generally needs to be generated from final energy at the location and time of demand by energy conversion.
Primary energy	Primary energy is the energy content of energy sources that are found in nature and have not yet been converted. A distinction is made between the – on a human scale – inexhaustible or renewable, fossil and nuclear energy sources.

Term	Definition
Secondary energy	Secondary energy is the energy content of energy sources that are generated from primary energy in one or more conversion steps. Within this project the output of useful thermal energy from a cogeneration process is described as secondary energy. Converted primary energy, e.g. coal, is used in a communal combined heat and power station. The combined heat and power station converts this energy into electrical and thermal energy. The thermal energy is then transferred from the station to its designated place, e.g. a district heating network. As soon as this energy arrives at the sub-station of the consumer it is defined as final energy.

1 Preface

1.1 The International Energy Agency (IEA)

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 29 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

1.2 The IEA Energy in Buildings and Communities Programme (EBC)

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes. The mission of the IEA Energy in Buildings and Communities (IEA EBC) Programme is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research. (Until March 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.)
The R&D strategies of the IEA EBC Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Buildings Forum Think Tank Workshops. These R&D strategies aim to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy efficient technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in five areas of focus for R&D activities:

- Integrated planning and building design
- Building energy systems
- Building envelope
- Community scale methods
- Real building energy use

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (☼):

Annex 1:	Load Energy Determination of Buildings (*)
Annex 2:	Ekistics and Advanced Community Energy Systems (*)
Annex 3:	Energy Conservation in Residential Buildings (*)
Annex 4:	Glasgow Commercial Building Monitoring (*)
Annex 5:	Air Infiltration and Ventilation Centre
Annex 6:	Energy Systems and Design of Communities (*)
Annex 7:	Local Government Energy Planning (*)
Annex 8:	Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9:	Minimum Ventilation Rates (*)
Annex 10:	Building HVAC System Simulation (*)
Annex 11:	Energy Auditing (*)
Annex 12:	Windows and Fenestration (*)
Annex 13:	Energy Management in Hospitals (*)
Annex 14:	Condensation and Energy (*)
Annex 15:	Energy Efficiency in Schools (*)
Annex 16:	BEMS 1- User Interfaces and System Integration (*)
Annex 17:	BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18:	Demand Controlled Ventilation Systems (*)
Annex 19:	Low Slope Roof Systems (*)
Annex 20:	Air Flow Patterns within Buildings (*)

Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: ☼ Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: ☼ Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: ☼ Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: ☼ Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy and CO_2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO_2 Equivalent Emissions for Building Construction (*)
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
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Annex 67: Energy Flexible Buildings
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Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings

Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings
Annex 73: Towards Net Zero Energy Public Communities
Annex 74: Competition and Living Lab Platform
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables
Annex 76: ☼ Deep Renovation of Historic Buildings Towards Lowest Possible Energy Demand and CO_2 Emissions
Annex 77: ☼ Integrated Solutions for Daylight and Electric Lighting
Annex 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
Annex 79: Occupant-Centric Building Design and Operation
Annex 80: Resilient Cooling
Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings
Working Group - Cities and Communities
Working Group -Building Energy Codes
Working Group -International Building Materials Database

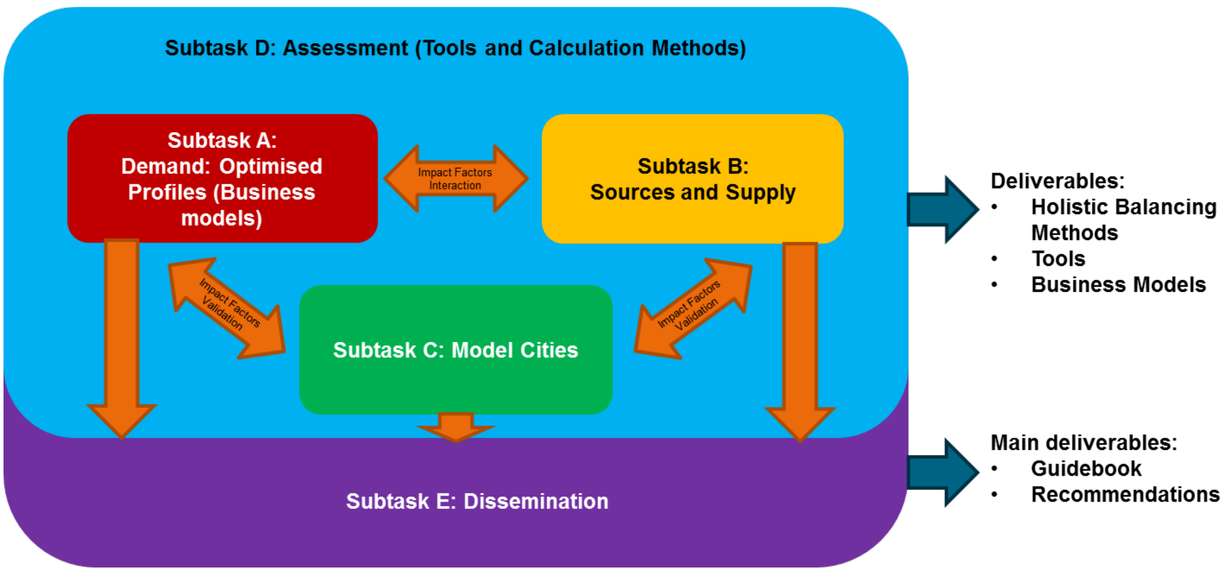

Figure 1 Structure of IEA EBC Annex 64 and organization of the different subtasks.

1.3 The IEA EBC Annex 64 – LowEx Communities

EBC Annex 64 was a three year international research project, which was initiated in an international definition workshop in September 2012 in Munich/Germany and started after a one year preparation phase with a working phase in mid-2014 and ended in mid-2017. The project was closed after the reporting in mid-2018.

The IEA EBC Annex 64 – LowEx Communities aims to demonstrate the potentials of low exergy thinking on a community level as energy and cost efficient solutions to achieve 100 % renewable and GHG emission-free energy systems. Central challenges are the identification of promising and efficient technical solutions for practical implementation. Aspects of future network management and business models for distribution and operation are as well essential for successful implementation and have been covered in the working phase. Aspects of transition management and policy will ensure the feasibility.

Within the project a discussion on appropriate additional indicators, supplementing the exergy assessment was initialised and finalized to obtain a common understanding of local potentials and supply options under the preconditions of local availability. In this context, the application of exergy analysis provides the necessary basis for greater local energy autonomy and impulses for local economy.

The main objective of the annex is to demonstrate the potential of low exergy thinking on a community level as energy and cost efficient solutions, in achieving 100 % renewable and GHG emission-free energy systems. The intention is to reach these goals by providing and collecting suitable assessment methods (e.g. holistic balancing methods). Furthermore, guidelines, recommendations, best-practice examples and background material for designers and decision makers in the fields of building, energy production/supply and politics are provided.

Specific objectives are:

- to develop and improve means for increasing the overall energy and exergy efficiency of communities through demand adapted supply and inclusion of renewable energy sources.
- to initialise a discussion to come to a common understanding of how to weigh high-exergy electricity for heating and cooling purposes under the preconditions of local availability.
- to identify the most promising and efficient technical solutions for practical implementation and aspects of future network management and business models for distribution and operation.

Countries which participated in the IEA EBC Annex 64: Austria, Denmark, Germany, Italy, the Netherlands, Sweden, USA and Turkey as an observer.

The work within Annex 64 was focused on both the theoretical and methodological tools as well as on modelling and on practical implementation aspects. The scope is clearly to evaluate the practical application of low-exergy approaches on a community scale. Thereby, the Annex gave input to further technology development, the understanding of system synergies and existing implementation barriers.

With this basis and to accomplish the above mentioned objectives, participants researched developments within the general framework of four fields.

- On one hand optimisation of the energy demand profiles and the resulting business models for such activities has a focus on the users and the energy utilisation within the built environment.
- On the other hand the optimised utilisation of (renewable) energy sources and optimised supply structures are focusing on the structure of the energy supply and the management of the involved infrastructure. For an optimised system both need to be regarded as an integral energy system.
- To visualise the possibilities and challenges from this approach, as well as the possible implementation of technologies, the realisation and the development of model cities, of realised cases, was an important part in the project.
- Finally, for an assessment of both the technologies and case studies, calculation methods and developed tools are further developed and evaluated based on a exergy assessment methodology description.

The knowledge transfer and dissemination activities of the project were focused on the collection and spreading of information on ongoing and finished work of the Annex.

Further information about the project can be found on the internet under:

www.annex64.org
or
http://www.iea-ebc.org/projects/project?AnnexID=64

1.4 Operating Agent

This international cooperation project has been coordinated by the operating agents

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This Guidebook of EBC Annex 64 is the result of a joint effort of many experts from various countries. We would like to gratefully acknowledge all those who have contributed to the project by taking part in the writing process and the numerous discussions. This cooperative research work is funded by various national sources and from industry partners. The authors would like to thank for the given financial support. A list of the participants within Annex 64 and their corresponding countries can be found in the Appendix. All participants from all countries involved have contributed to the guidebook. However, the following Annex participants have taken over the responsibility of writing the chapters:

Dietrich Schmidt	Editor, operating agent, contributed to almost all chapters, main author of chapters 1, 2 and 7
Christina Sager-Klauss	Operating agent and Subtask E coordinator
Anna Kallert	Editor, contributed to almost all chapters, especially chapters 4, 5, 6, 7 and appendix B and C
Sabine Jansen	Subtask A coordinator, main author chapter 3, contributions to chapter 5
Forrest Meggers	Subtask B coordinator, especially chapters 4 and 5.3
Ralf-Roman Schmidt	Subtask C coordinator, especially chapter 5
Charlotte Maguerite	Subtask C coordinator, main author of chapter 5, contributed to almost all other chapters, especially chapters 3, 4.2 and 6.1
Ivo Martinac	Subtask D coordinator, especially chapter 6
Genku Kayo	Subtask D coordinator, main author chapter 6, contributed to chapter 4.1
Marek Brand	Contributed especially to chapters 4.2 and 5.3
Oddgeir Gudmundsson	Contributed especially to chapter 4.2
Klaus Lund Nielsen	Contributed especially to chapters 4.2, 5.3 and 6.1
Maria Harrestrup	Contributed especially to chapter 5.3
Svend Svendsen	Contributed especially to chapters 4.2, 5.3 and 6.1
Janybek Orozaliev	Contributed especially to chapters 5.3
Isabelle Best	Contributed especially to chapters 4.2 and 5.3
Marc Baranski	Contributed especially to chapters 4.1, 5.2 and 6.1
Roozbeh Sangi	Contributed especially to chapters 4.1, 5.2 and 6.1
Saeed Saydi	Contributed especially to chapters 4.1, 5.2 and 6.1
Frank Dammel	Contributed especially to chapters 4.3, 5.3 and 6.1
Paul-Michael Falk	Contributed especially to chapters 4.3, 5.3 and 6.1
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Michiel Fremouw	Contributed especially to chapters 3, 4.2 and 5.4
Eric Willems	Contributed especially to chapters 4.1, 4.2 and 6.1
Peter Op't Veld	Contributed especially to chapter 6.1
Hongshan Guo	Contributed especially to chapters 4 and 5.3

Frederica Zagarella	Contributed especially to chapters 5.3, 5.4 and 6.1
Marta Giulia Baldi	Contributed especially to chapters 5.3, 5.4 and 6.1
Paola Caputo	Contributed especially to chapters 5.3, 5.4 and 6.1
Xiaochen Yang	Contributed especially to chapters 4.2, 5.3 and 6.1
Siir Kilkis (Observer)	Contributed especially to chapters 4.3, 5 and 6

This report is a summary of the conducted work of EBC Annex 64 (www.annex64.org).

2 Introduction

2.1 Background and Motivation

The energy demand for heating and cooling in the building sector is responsible for more than one third of the final energy consumption in Europe and worldwide. Commonly this energy is provided through different fossil fuel based systems using combustion processes. These combustion processes cause greenhouse gas (GHG) emissions, which are regarded as one of the core challenges in fighting climate change and realizing the energy transition. National and international agreements (e.g. the European 20-20-20-targets, the Kyoto protocol or the Paris Agreement with the aim of limiting global warming to 1.5 °C compared to pre-industrial levels) limit the GHG emissions of industrialized countries respectively for climate protection. Country specific targets are meant to facilitate the practical implementation of measures. While a lot has already been achieved, especially regarding the increased share of renewables in the electricity system, there are still large unutilised potentials in the heating and cooling sector and especially on the community scale. Exploiting these potentials and synergies demands an overall analysis and holistic understanding of conversion processes within communities. Here the exergy concept is applied to archive better overall energy system designs.

As part of the project, communities are defined as a larger group of buildings, such as a block or a neighbourhood which are characterised by a wide range of energy demands in different sectors, for instance heating and cooling demands, and lighting and ventilation. Different energy quality levels (as part of exergy) are required as heat or cold flows or as electricity and fuels. On the community level, there is the possibility of supplying this energy through different sources; e.g. low-temperature heat from geothermal sources at a low exergy level or through roof-top photovoltaics as high-exergy electricity. The fluctuating electricity supply from renewable electricity production e.g. wind and PV power offers both chances and challenges for future community energy systems. The interaction between (matched) energy demand and available (fluctuating) energy sources at different quality levels (exergy factor), especially for covering the heating and cooling demand, has to be solved at a local level, within the community (Schmidt and Sager 2010).

To identify potential savings and synergies a holistic analysis of energy flows is necessary. This allows the detection of available quality levels. These are taken into account, from generation to final use, to significantly reduce the share of primary or high-grade fossil energy that is used and to optimise exergy efficiency (Ala-Juusela 2004). In practical implementation, advanced technologies must be adapted and further developed to realise the identified potentials. At the same time, as the use of high quality energy for heating and cooling is reduced, there is more reason to apply integral approaches in regards to other processes in which energy/exergy is used in communities.

The results of the international cooperation activity EBC Annex 49 "Low Exergy Systems for High-Performance Buildings and Communities" (Torio and Schmidt 2011) emphasise the great potentials in exergy management. For this reason, the results achieved during the course of this earlier activity provided the necessary basis for exergetic investigations which have been performed within the framework of the work of EBC Annex 64 and are reported here. Experiences and case studies from other international cooperation activities as EBC Annex 51 "Energy efficient communities" (Jank et al. 2013) show the opportunities in targeting especially the community scale.

2.2 The LowEx Approach for Communities

Basically, the physical property "exergy" can be described as a product of energy and "energy quality". The higher the temperature of a heat flow is above reference temperature, the higher the energy quality. To simplify thermodynamic principals for the scope of this activity it can be stated that: The lower the temperature of a thermal energy supply flow for heating, the lower its energy quality is and, therefore, the associated exergy flow (Dincer and Rosen 2007), (Torio and Schmidt 2011), (Schmidt and Kallert 2017). In this way exergy is utilised to optimise the efficiency of a community supply system. This is called the low exergy (LowEx) approach. The LowEx approach entails matching the quality levels of energy supply and demand in order to optimise the utilisation of high-value energy resources, such as combustible fuels, and minimise energy losses and irreversible dissipation (internal losses) (Torio and Schmidt 2011).

On the community scale, different types of supply systems require different supply temperatures. To obtain the maximum output from a given primary energy flow, different temperature levels can be cascaded according to the requirements of the building typology and technology. This demands an intelligent arrangement and management of the temperature levels and flows within the system. Bi-directional concepts and short term storage can be elements of a system which is not only energy efficient, but also exergy efficient. As high-exergy resource electricity plays a special role within the evaluation processes, it is feasible, on an exergy basis, to weigh the impact of extra electricity use, for instance for pumping or ventilation, on a thermodynamically correct basis against the heat and cold applications. On this basis, a discussion on a proper and workable set of indicators will have to be held to reflect aspects of renewable and non-renewable electricity and fluctuating supply in electrical energy systems.

Current projects and analysed cases show the potential in terms of improved energy efficiency and GHG emissions reductions. Some successfully conducted studies indicate a cost reduction potential for innovative low temperature heat grid community solutions based on the exergy thinking concept and a CO_2 free heat delivery process (e.g. Schmidt et al. 2016). These promising cases are analysed in detail and described in this report.

From all this a so-called LowEx Community could be defined as a community for which the energy system is designed in such a way that exergy destruction for the required energy services, including space heating and domestic hot water preparation is minimised.

2.3 Target groups

This report is addressing the three main target groups of the Annex

- decision makers from the energy supply and technology industry
- decision makers within communities
- project developer
- housing companies.

The key findings on of the Annex activities are condensed in order to simplify public access and use of the results. In turn, the report is aimed to be an easy to understand and practical, applicable design guideline for key people in communities and to support them to integrate innovative technologies into their future design approaches. In this regard, questions from the named target groups on the arguments for taking action for a possible change of the energy system within the community are considered. So, also issues on what actions should or should not be taken with regard to the community's energy system are considered within this report. This implies further the arguments on the fulfilment of the community's conditions for the implementation of a new technology.

These questions are answered in this report with a focus on decision makers' point of view. This will cover issues on how to implement advanced supply technologies at a community level and how to optimise supply structures to ensure reduced costs for the system solution, while providing a high standard of comfort to the occupants of the buildings. This integrates explanations of the multilevel approach with easy-access methods to exergy-thinking in urban planning and detailed guidance to sophisticated exergy modelling.

So this report is intended to support designers for the integration of concepts into design strategies, systems and technological solutions as well as decision makers and urban planners to integrate low exergy technologies into energy transition strategic processes and policies. The dissemination of documents and other information is to be focused on providing practitioners with research results.

More detailed results for satisfying the needs for other groups as scientists are published as separate reports via the named project homepage
www.annex64.org.

2.4 Main objectives and layout of this report

This report represents a summary of the results obtained during the course of the EBC Annex 64 work. In this context, the main considered objectives and challenges of EBC Annex 64 are:

- Application and further development of the low exergy (LowEx) approach, which includes the enlargement of LowEx approach for communities, the demonstration of potential of low exergy thinking on a community level to increase the overall energy and exergy efficiency of communities
- Identification and application of promising technical solutions via the integration of LowEx system components (generation, distribution and supply) and the practical implementation and aspects of future network management as well as business models for distribution and operation
- Assessment methods and tools via the application of exergy analysis as a basis for providing tools

as well as a collection and merging of suitable assessment methods, including the further-development of assessment tools and methods for various stages of planning

All the above mentioned topics are treated in more detail in the following chapters of this report.

After a presentation of the general framework of the EBC Annex 64 activity within the IEA in chapter 1 and an introduction into this report in chapter 2, the next chapter 3 describes the use of exergy analyses in different stages of the development of sustainable community energy supply systems and points the role of exergy as an indicator for achieving that kind of systems. Moreover, it is explained further and related to other performance indicators for energy systems, such as financial aspects and CO_2 emissions. Thereby, the role of "exergy thinking" principles for use in the early development phase is explained and a simplified exergy analysis approach, in order to further improve the exergy performance, is presented. This chapter on general design principles concludes with an easy to follow ten-step-approach for the application of exergy analyses. In chapter 4, issues on technology implementation with regard to an exergy optimised design are presented. Starting with a description of the estimation of various energy demands in the built environment, the chapter also considers new challenges in the sector coming from e.g. zero energy buildings and their special boundary conditions on urban infrastructures because of the fluctuating feed-in of energy into the grids. Here the topic of interface definition is of importance and the question where decentralised or centralised systems are of advantage is taken into consideration. This technology chapter concludes with a brief description of regarded key technologies. Chapter 5 gives insights into the analysed case studies on various scales. Ranging from building scale cases, via a number of district scale cases to cases on the city scale analyses are presented and summarised. The topic of possible business models in combination with new technologies is also covered here. In chapter 6, various models and tools for energy system design with respect to exergy which have been analysed during the course of the annex are briefly described and analysed. To enable the reader to make a suitable and case specific selection a general analysis of the models and tools based on their specific strength, weaknesses, opportunities and possible threats is presented.

3 Exergy Thinking & Exergy analysis framework

The exergy concept can be used in the development of sustainable community energy supply systems. This can be done from the early stage until the detailing and optimisation phase. First, by considering exergy principles in the development of the potential solutions more favourable solutions can be obtained. In later stages of a project, exergy can be used to further improve and optimize the energy systems considered.

This chapter describes the use of exergy in different stages of the development of sustainable community energy supply systems. To start with, in section 3.1 the role of exergy is explained, and related to other performance indicators for energy systems, such as financial aspects and CO_2 emissions. In section 3.2, the different phases of energy system design are explained and the applicable role of exergy for each stage is introduced. After that, the exergy thinking principles for use in the early development phase are explained in section 3.3, and a simplified exergy analysis approach for further improvement of the exergy performance is presented in section 3.4. The chapter ends with conclusions in section 3.5.

This chapter also represents the outcome from discussions held within the Annex 64. These discussions where partly previously addressed in (Jansen and Meggers 2016). Furthermore, various research outcomes and publications are used in this chapter, such as (Jansen 2015 and Kallert 2018).

3.1 Exergy as an indicator for sustainable community energy systems

The term exergy is often mentioned together with the term sustainability. This section addresses some discussions and considerations on how these two can be related, since they are not inherently the same (see also Dincer and Rosen 2013).

Exergy is a thermodynamic concept that defines the thermodynamic work potential of a system (Moran and Shapiro 2004). Exergy analysis provides critical insight into the maximum (work) potential of energy resources. This insight cannot be obtained with energy analysis based solely on the first law of thermodynamics (see also Torio and Schmidt 2011). When exergy losses are minimized, the required input of high-quality resources is also minimized. Exergy analysis can thereby minimize fossil fuel inputs or improve renewable and sustainable systems.

However, exergy analysis does not inherently include other objectives, such as maximizing the use of renewables or minimizing emissions, nor are costs inherently the same as exergy, although there may be a relation between these. Especially the relation between exergy and renewability or CO_2 emissions is often discussed.

This section presents the outcome discussions of the Annex 64 experts on the role of exergy analysis in the context of communities and districts. Firstly, we discuss the definition of exergy and its related aspects as an indicator of the performance of an energy system. Secondly, we discuss the relation between exergy on one hand and renewability and CO_2 emissions on the other. And lastly we relate exergy to other energy objectives for buildings and communities.

3.1.1 Exergy definition

Although exergy thinking in a broader sense is also possible, exergy is a thermodynamic concept that defines the potential of any form of energy to perform work: Exergy is the maximum amount of work obtainable from a system (or amount of energy) by bringing this into equilibrium with the environment (Moran and Shapiro 2004).

The term "exergy" was first introduced by the Slovenian professor Zoran Rant (Fritzsche et al. 1956) and is derived from the Greek words ex (from) and ergon (work). Several different terms (e.g. availability or workability) can be found in the literature (Frangopoulos 2009; Dincer and Rosen 2013; Bargel 2010).

Exergy is thus a thermodynamic concept, which quantifies the work potential of a given form of energy. It is based on the properties of a system as well as on the properties of the surrounding 'reference environment' Tref (see section 3.4 as well as Torio and Schmidt 2011).

Exergy consists of different components, as described by many authors (e.g. Bejan et al. 1996). The exergy of a given system consists of:

- Kinetic exergy (due to the system velocity measured relative to the environment)
- Potential exergy (due to the system height measured relative to the environment)
- Physical exergy (due to the deviation of the tem-

perature and pressure of the system from those of the environment), includes the mechanical exergy (associated with the system pressure) and the thermal exergy (associated with the system temperature)
- Chemical exergy (due to the deviation of the chemical composition of the system from that of the environment).

For energy systems in the built environment mostly physical exergy is regarded in the analysis. For various systems also the chemical exergy of fuels can be relevant. For this aim usually the standard chemical exergy is taken from the literature (e.g. Szargut 2005)

3.1.2 The Quality factor or Exergy factor

The quality factor (q or Fq), also referred to as exergy factor (Fex), is defined as exergy content divided by energy content (see equation 1)

$$F_q = \frac{Energy}{Exergy} \qquad \text{Equation 1}$$

The quality factor of heat depends on the temperature of the heat and its calculation is based on the Carnot cycle (Carnot 1824). For heat at constant temperature (isothermal process), equation 2 should be applied.

$$F_{q(Q)} = \frac{Exergy}{Heat} = \frac{Ex_Q}{Q} = \underbrace{\left(1 - \frac{T_0}{T}\right)}_{\text{Carnot factor}} \qquad \text{Equation 2}$$

For heat related to matter, where the temperature of the matter drops as heat transfer takes place, equation 3 is applicable (as long as a constant heat capacity is assumed). For more explanation on the exergy of heat the Annex 49 guidebook (Torio and Schmidt 2011) can be consulted as well as various publications on exergy application in the built environment can be used (e.g. Schmidt 2004a; Shukuya 2013; Jansen 2013, Kallert 2018) and many textbooks on thermodynamics can be consulted (e.g. Moran and Shapiro 2004; Bejan et al. 1996).

$$Ex = Q_s \cdot \left(1 - \frac{T_0}{T_2 - T_1} \cdot \ln \frac{T_2}{T_1}\right) \qquad \text{Equation 3}$$

Lastly, the quality factor of fuels can be found in literature (for example Szargut, 2005) and can be given in relation to the higher- or the lower heating value, according to equation 4 (Kallert, 2018).

$$F_{q(HHV)} = \frac{Ex_{ch}^{LHV}}{HHV^{fuel}} \qquad \text{Equation 4}$$

In line with the quality factor or exergy factor, 'low-ex' or 'low quality' energy sources refer to sources with a small exergy content relative to the energy content, that is: with a low quality factor. A 'low-exergy' energy is a source that can produce little work, relative to its energy content, or that theoretically requires little work to be produced. Basically, it can be said that the higher the temperature of a heat flow is above the reference temperature (which is in many cases equal to the ambient temperature, see further in this chapter), the higher the energy quality (Torio and Schmidt 2011). Especially in connection with buildings that require only low temperatures for space heating and hot water production, the utilisation of fairly low tem-

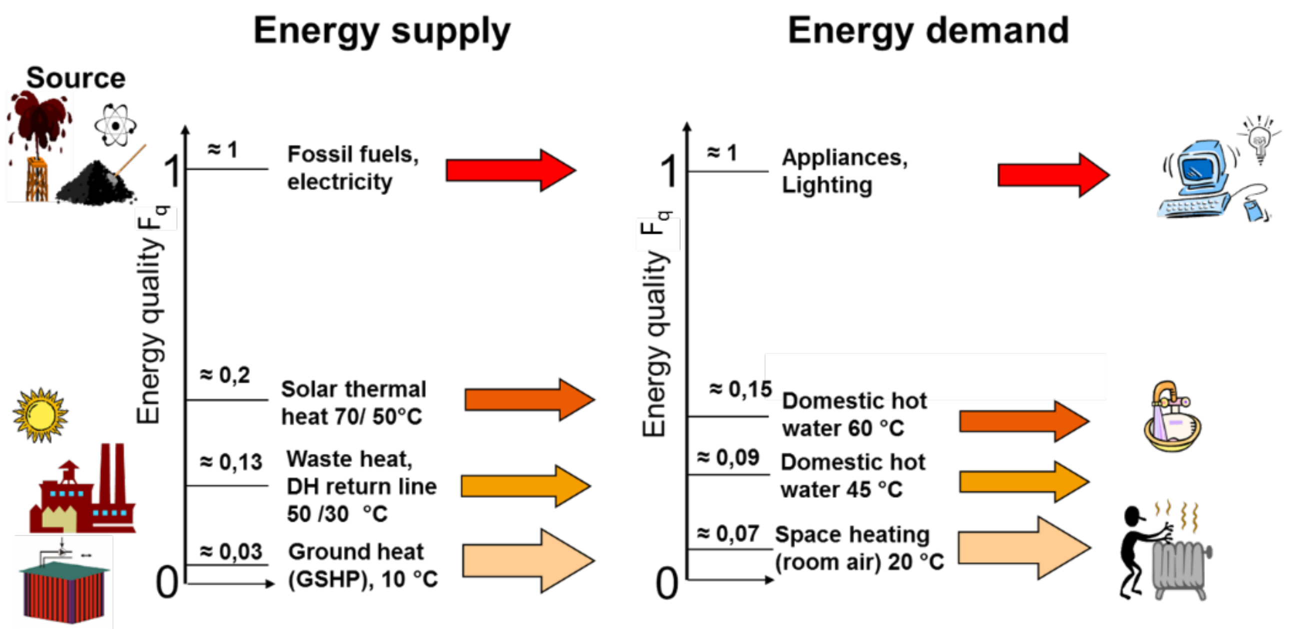


Figure 2 Different quality factors (Fq) of demand side and supply side for quality matched low temperature district heating supply (Kallert et al. 2017; Ala-Juusela 2004)

peratures (such as geothermal heat and solar heat) offer great possibilities for high efficient supply (see Figure 2).

3.1.3 Exergy as performance indicator

When an amount of energy with high exergy content (for example natural gas) is converted into the same amount of energy with low exergy content (for example space heating), exergy is destroyed.

Hence: exergy provides an indicator of how much of the full (thermodynamic) potential of an energy input is actually being used in a given system or process.

If exergy destruction is minimized, fewer resources are needed. Moreover, the exergy destruction shows us how much resources could (theoretically) be saved. This is why exergy is an important indicator for the sustainability of energy systems.

However, in real systems the final aim is rarely to use the maximum potential of our resources. Other criteria are usually more important such as costs, emissions, environmental impacts etc. Exergy can be linked to these, but is not inherently connected.

Some literature studies have tried to extend exergy considerations to other objectives, as is also mentioned by Favrat et al. (2008). Favrat takes the approach of regarding exergy according to its thermodynamic definition as described previously, looking at exergy as one indicator amongst others. The connection to other objectives, such as primary energy or emissions, should be made through the exergy optimization steps. This approach is also taken by the Annex 64 experts.

To consider that in some cases there can be reasons that justify the destruction of exergy, a LowEx community was defined as "a community for which the energy system is designed in such a way that exergy destruction is minimized, or that all exergy destruction is justified by other reasons (e.g. economic / social, other sustainability reasons)".

3.1.4 Exergy of renewable resources

Sometimes renewable resources are referred to as 'low-ex' resources. This is understandable, since renewable resources are often freely available. Also sometimes the argument mentioned is that exergy destruction of renewables is less problematic than exergy destruction of non-renewables. However, based on the thermodynamic definition of exergy, not all renewables are low-ex sources. This is important to keep in mind, since if we want to fulfil all needs with renewable resources, we must also use them to the best of their potential, and therefore consider their exergy potential.

Figure 3 shows the chain of exergy utilization for a building and how renewable production can be a key input into the analysis (Schmidt 2004). Still, the analysis itself is independent of whether the exergy flow is from a renewable source.

In other words, it can be the case that an energy system is fully based on renewables, but is exergetically very inefficient. It must be mentioned that this is an advantage of an exergy analysis: it can also be used to maximize the use of the potential of our renewable resources. Hence, in addition to the exergy performance, the renewability is a separate indicator.

Another criterion to classify energy inputs for the simultaneous assessment of fossil and (fluctuating) regenerative energies is the 'storability criterion', introduced by (Jentsch 2010). As part of this assessment approach, a distinction is made between storable and non-storable energy forms. For evaluation, the primary energy carriers are used, which are affected by ambient conditions.

The storability criterion refers to the fact that some energy sources can be stored, such as coal, sensible

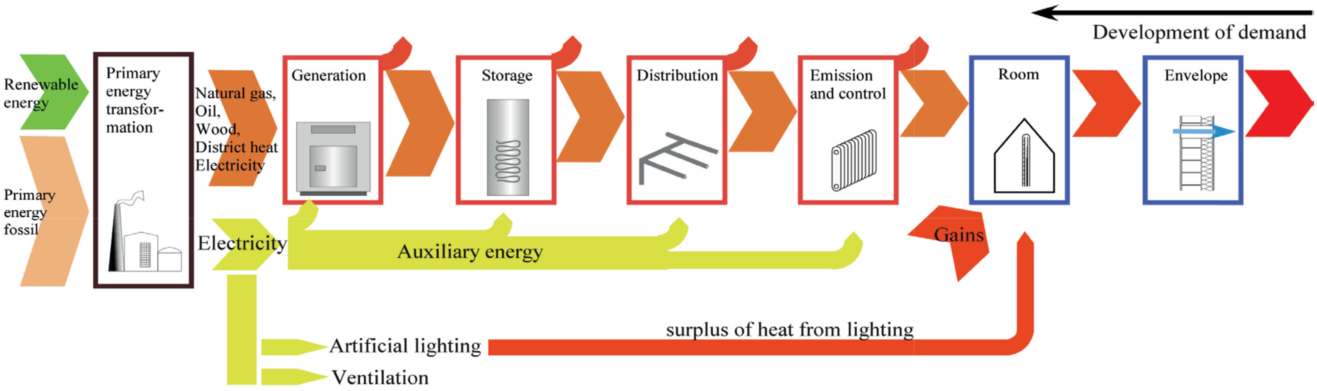


Figure 3 Chain of exergy utilization for a building (Schmidt 2004).

heat or gas, while others by nature cannot. The latter include for example solar radiation or wind: energy flows that are lost for utilization anyhow once they have not been used directly. These sources need to be converted to a storable form of energy, if they are to be used later on. It is obvious that storable forms of energy have more value in some respect than non-storable forms of energy. However, this value is not equal to the thermodynamic value of exergy (work potential). Also in this case the most logical approach is to consider the storability criterion as a separate classification of an energy input, in addition to its exergy content. Subsequently, it can then be argued that exergy destruction of non-storable forms of energy is more easily justified than exergy destruction of storable forms of energy.

As described in more detail in Jansen and Meggers (2016), it is suggested to use the thermodynamic definition of exergy in order to obtain insight on how well the potential of resources is being used - both renewable, non-renewable, storable or non-storable, and use these other indicators separately. These can potentially justify exergy destruction, but then it will be an explicit justification without losing the insight in the potential from the exergy analysis.

3.1.5 The influence of chosen system boundaries

Another important aspect when evaluating exergy input is the system boundary considered for the analysis. According to the thermodynamic definition, the work potential is independent of any history of how this energy is produced. In other words, 1 kW of electricity is 1 kW of exergy, independent of whether it comes from solar energy or from a gas fired power plant. To understand the amount of exergy that was needed to produce this kW of electricity, the chain of preceding processes has to be analysed. This means that for exergy assessment the definition of the boundaries for calculation has decisive influence, since exergy destruction occurs at each step of the energy conversion chain even if energy losses were ideally zero (as it is for example in the case of the heat emission system to the room air). Resulting, the choice of inconsistent boundaries for similar energy systems can lead to significantly different assessment results and misleading conclusions.

For comparison studies therefore, the system boundaries should preferably be the same and at least be very clearly defined. However, for particular studies the relevant system boundaries can differ. Basically it has to be distinguished whether the investigations are aimed at a process evaluation of e.g. a single supply unit (for example optimisation of a heat pump) or are targeted on a comprehensive system comparison of different supply scenarios (e.g. building energy system or community supply system). (Kallert 2018). For solar systems often the methodology described by Torio and Schmidt (2011) (see also Torío et al. 2009; Torío 2012;Jentsch 2010) is used, where the temperature of the output of the solar system (e.g. collector) is used as system input. It should be noted that there are different approaches for this, and when optimizing the use of solar radiation, broader system boundaries are more suitable (Jansen and Meggers, 2016). To summarize: for different purposes different system boundaries may be applicable. It is very important however to clearly define and describe the system boundaries for all analyses, as these greatly influence the results.

3.1.6 Exergy related to other energy objectives for buildings and communities

The aim for a sustainable built environment has been translated into various methods or approaches for reaching this goal, such as for example the "passive house'' approach or the Net Zero Energy Building Directive (nZEB). How does exergy relate to these approaches?

As stated in the beginning, exergy thinking and exergy analysis leads to an optimal use of energy resources, and as such, exergy optimization can play a role connected to these other approaches. As an example, the passive house strategy is compared to an exergy approach below (from Jansen and Meggers 2016):

Passive house buildings have the objective to be supplied by heat from mainly passive gains. The requirement is that the remaining demand for space heating does not exceed 15 kWh/m² on an annual basis. This demand is reduced to such a degree that it justifies an 'exergy inefficient' way of producing this small amount of heat, for example with a conventional boiler or with joule heating. Placing a highly exergy efficient but also highly expensive component to supply this small demand could be undesirable. In other words, the total primary energy input needed for a passive house is low due to the maximum reduction of the demand and not due to an exergy efficient energy chain. The passive house is actually an example where the energy objective to reduce heat loss to an explicit level is independent of consideration for upstream sources of heat and potential exergy matching.

An exergy analysis can show how rather than 0.5 m thick walls, an efficient heat pump connected to a low

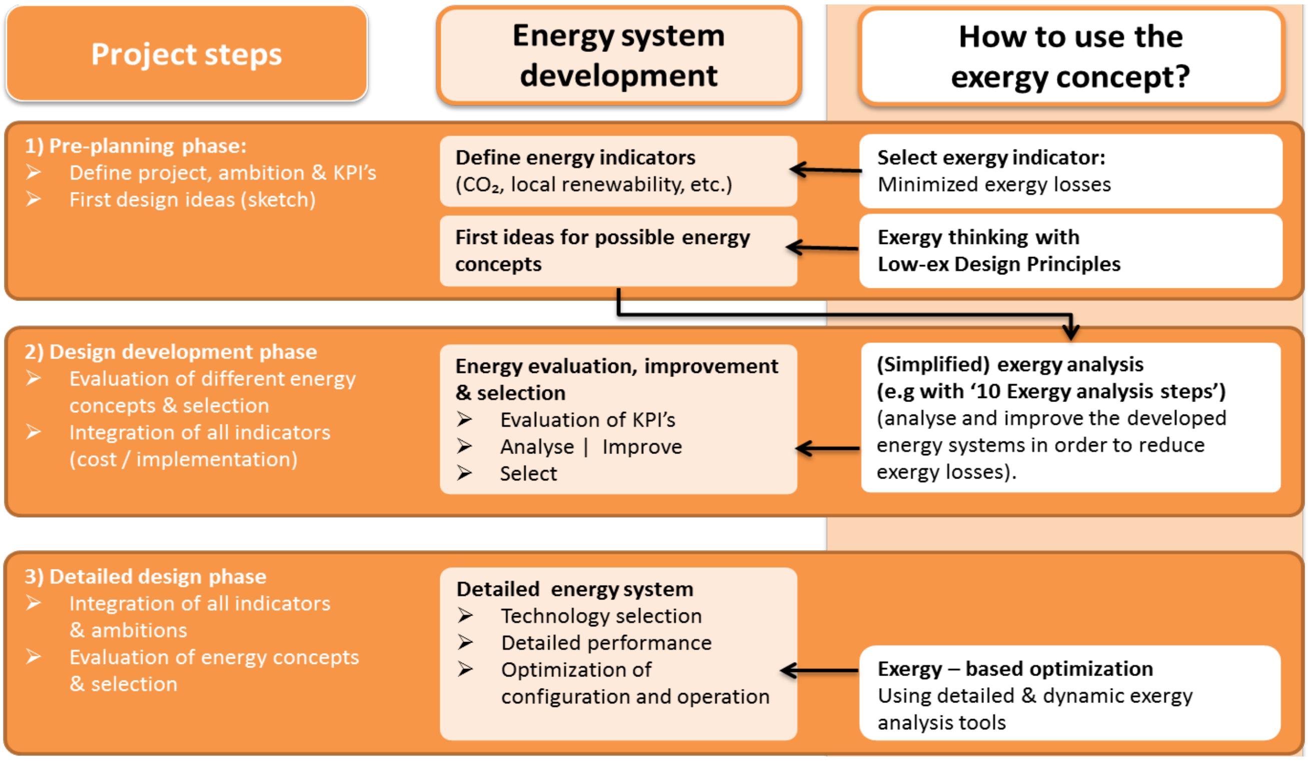


Figure 4 Overview of the different steps in the development of community energy systems, with related exergy approaches.

temperature radiant heating system may result in the same primary energy input as the operating passive house (Meggers et al. 2012). But again, outside the exergy analysis, the cost of the heat pump must be considered in comparison to the use of insulation. Still, underneath these costs, the exergy analysis provides the method for comparing the true effectiveness of each within the chain of energy utilization.

3.2 The role of exergy in the different phases of developing community energy systems

Now that we have discussed the definition of exergy and the relation with other performance indicators, we will look at how to apply the exergy concept in the planning and development of community energy systems.

Three phases can be distinguished: firstly, the pre-planning phase, where ambitions are set and the first options for the community energy system are explored and roughly assessed; secondly the design development phase, which leads to a draft design of the community energy system. After that a detailed design phase will start, where refining and optimization takes place. This will lead to a detailed design of the community energy system. In all phases exergy can play a role:

Phase 1: Pre-planning phase: Exergy thinking by using exergy principles

In the pre-planning phase the ambitions are set and various options for the community energy system are explored and roughly assessed. This development can be partly based on exergy thinking: exergy principles can be applied to the first ideas and options for the community energy system. These principles are further explained in section 3.3.

Phase 2: Design development phase

One or more draft energy configurations can be further developed and exergy analysis can play an essential role in this phase. The exergy analysis shows in which configuration and in which component the biggest exergy losses occur. This means the system can be improved and insight can be obtained on whether a system can be improved and how. This leads to a choice of a most promising energy configuration and a first optimization of it. In section 3.4 the necessary steps to carry out a basic exergy analysis & exergy optimization cycle are explained in 'ten exergy analysis steps'.

Phase 3: Detailed design phase

When designing the final configuration and operation of a community energy system, exergy can also play a role. In this case, more detailed exergy analyses can be used. These are in principle based on the 10 steps described under 3.4, but are more complex and can be based on various (dynamic) energy simulation tools. The different tools are described in chapter 6.

In the figure above a scheme for the process of developing a sustainable community energy system is shown, with the relevant way of using the exergy concept in each phase. The Low-Ex design principles are described in section 3.3; the '10 exergy analysis steps' can be found in section 3.4

3.3 Low-ex Design Principles for pre-planning of community energy systems

To create an exergy efficient community system, the first step is to include 'exergy thinking' in the first development phase. Exergy thinking can influence the layout and design of the energy supply systems. In general, the aim is obviously to support the development of exergy conscious draft configurations of community energy supply systems, where exergy losses are minimized. Exergy thinking principles are for example presented in thermodynamic handbooks (e.g. Bejan et al. 1996), previous Annex work (Torío and Schmidt 2011), and Jansen (2015). These are complemented with new insights and examples into the following principles:

1. Reduce exergy demands
2. Match temperature levels
3. Exergy smart storage
4. Use high-quality sources effectively
5. Avoid exergy destructive processes
6. Avoid large chains of components

They are further discussed on the following paragraphs.

3.3.1 Reduce exergy demand

The first step is to reduce the demand for high quality energy. This step is similar to the well-known first step of the 'trias energetica' (Lysen et al. 1996), but it goes further. By distinguishing between the different qualities of the different demands, the focus should be on reducing the 'high quality demands':

i.e.; when optimizing exergy it is for example more important to minimize the need for artificial light (which needs high quality electricity) than to minimize the need for space heating, which is low quality energy that could be supplied with less exergy input.

Note: The idea is not to maximally reduce the exergy demands; there will be an optimum between reducing demands and exegetically smart supply systems.

3.3.2 Use available (waste) exergy flows & exchange

Make an inventory of available flows of waste- and renewable energies. For a community energy system this means that also exchange of heat between different buildings functions can be very relevant.

Waste flows can include:

- Heat from data centers
- Heat from waste water or waste water treatments plants
- Heat from surface water
- Waste heat from cooling facilities (supermarkets, offices)
- Heat from greenhouses in summer
- Etc.

Currently also unconventional sources are investigated within the PLANHEAT project (www.planheat.eu). These include for example heat from underground (metro).

In Figure 5 an example of energy potentials for an urban area is shown. This example displays the potentials from a study on sustainable community energy system for a new area in Amsterdam (Strandeiland 2018), which will be a high density urban area of 8,000 dwellings and 150,000 m² of non-residential buildings.

3.3.3 Match the quality levels of demand and supply

The principle of matching quality levels is the basis of exergy thinking: Use low-ex sources for low-ex demands. This principle means the same as: use the lowest quality energy input possible. It is the easiest way of minimizing exergy losses: by choosing a source that closely matches the desired output. It is also the most often mentioned exergy principle in literature (Ala-Juusela 2004; Torio and Schmidt 2011; Schmidt 2004 and many more). It can be further elaborated into the following more practical recommendations (as listed by Jansen 2013):

a) **Use low-temperature heating (LTH) and high-temperature cooling (HTC).**
   The heating and cooling demand is a very low exergy demand, which in principle requires little 'high quality' input. When this heating and cooling demand is supplied with close temperatures at the emission system (e.g. floor heating), there is minimum exergy destruction between emission system and the actual demand. Obviously, if this heat is still supplied with an electrical boiler or a gas fired boiler, the exergy losses will occur there and there is no advantage in using low temperature heating.
b) **Minimize temperature differences when exchanging heat.**
   This is very important for all heat exchange processes: do not exchange heat with a large tem-

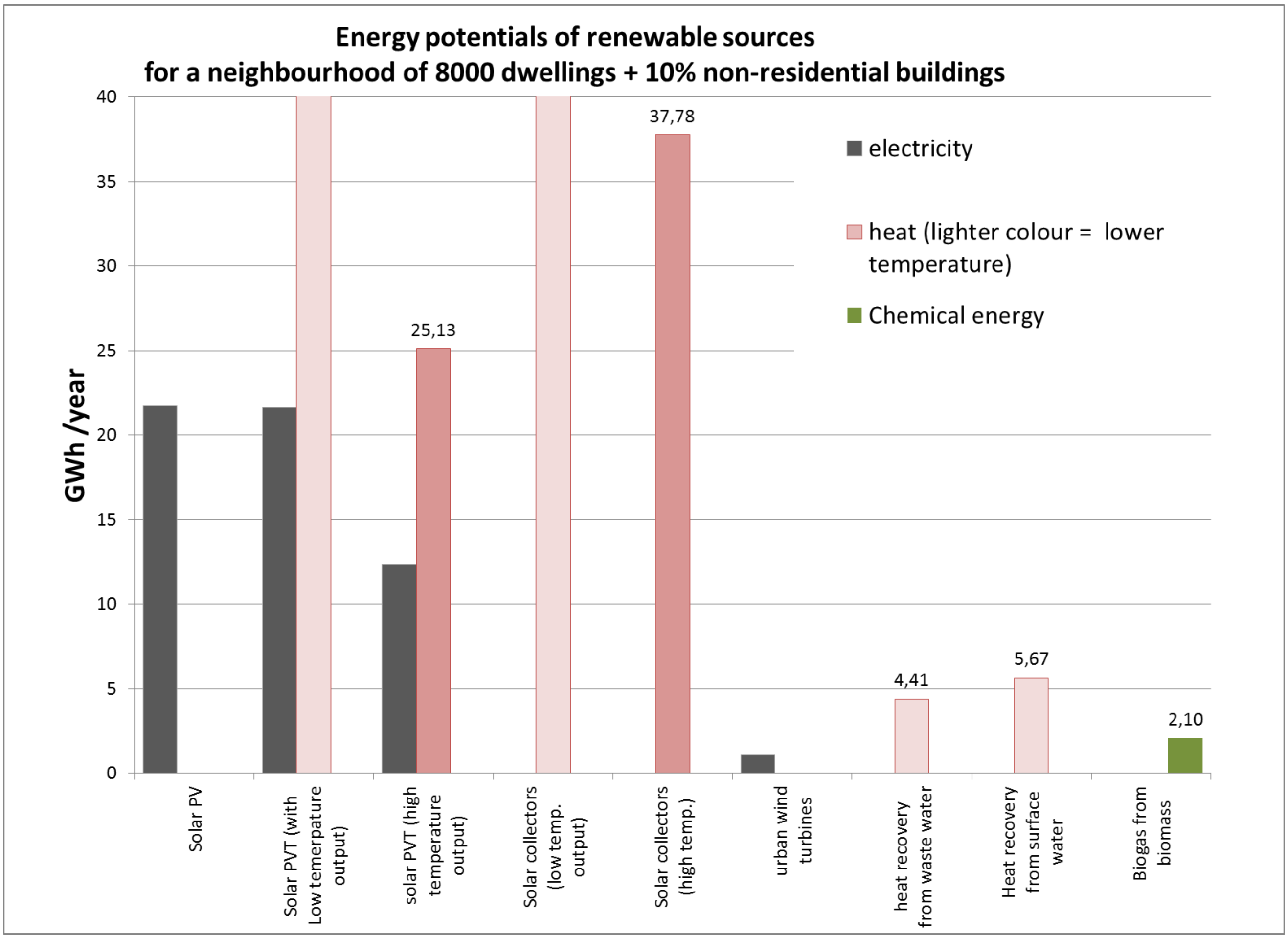


Figure 5 Graph showing the results of energy potential study for a new urban area (Strandeiland, Amsterdam). The colours display type of energy and temperature level / hence exergetic quality. Solar energy potentials are based on available roof surface.

perature difference. This also explains why counter flow heat exchangers are thermodynamically better than parallel-flow heat exchangers: the temperatures of the 'source' flow and the 'load' flow are closer to each other.

c) Use low-temperature energy flows existing in or around the building.

These energy flows include for example the heat from exhaust air or domestic hot water return, possible nearby surface water or waste water from industry.

d) Use the cascading principle.

Often the principle of cascading is proposed as a means to meet demands at multiple temperature levels in an exergy efficient way (Tillie et al. 2009; Torio and Schmidt 2011). In principle, cascading refers to the use of high-temperature heat flows for high-temperature demands, and the returning flow of this first demand to meet demands at lower temperatures. At the building level cascading can theoretically be applied between the demand for domestic hot water (DHW) at 60 °C and space heating at ca. 30 °C. For districts often the cascading within district heating networks is suggested.

It is very important to take into account that, in order to be exergetically more efficient, it is essential that the heat supply really benefits from this cascade:

- If the total heat demand of the total cascade is still supplied by a boiler, there is no benefit and exergy losses are still the same.
- If the lower return temperature results in a more efficient use of the primary energy in for example a combined heat and power (CHP) plant, primary energy use can be reduced. The gains are relatively small in this case.
- If the lower temperatures can be supplied with low temperature sources (such as solar thermal energy or low temperature waste heat which would otherwise not be used), there can be additional savings on high quality energy.

In Figure 6 a visualisation of the cascading principle is shown. It shows that the highest saving on (primary) energy input is achieved when previously unused waste heat starts being used. Further improvements can be achieved with cascading, but this is a smaller improvement. However, if additional low temperature waste heat can be used, the additional gains can be substantial.

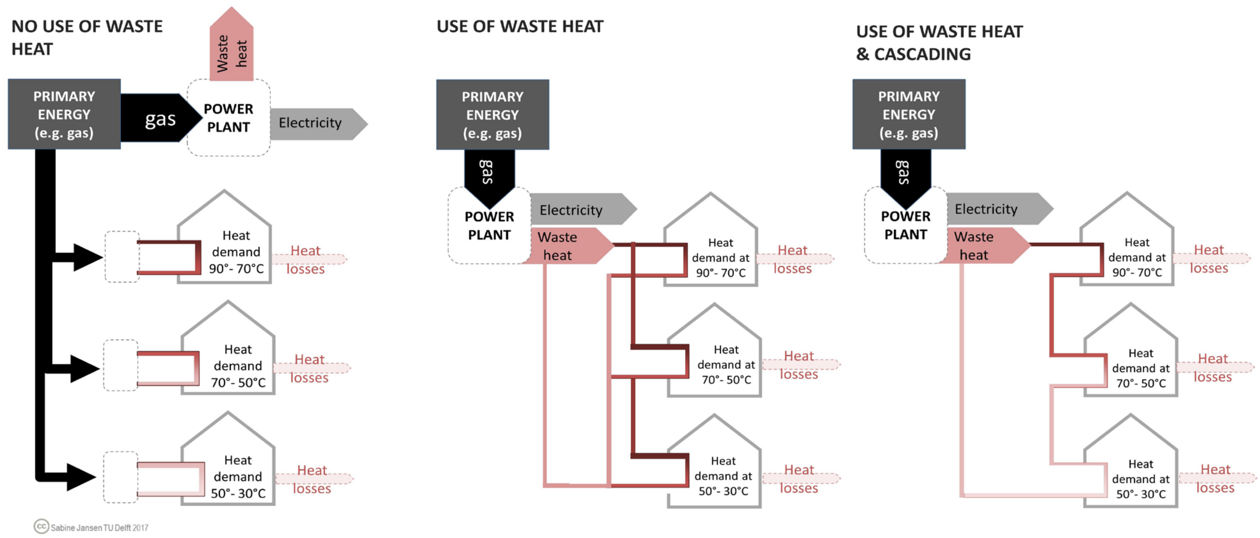


Figure 6 Scheme of the use of waste heat and the cascading principle: The left figure shows the traditional gas supply for a power plant and heat supply with gas boilers in buildings; the middle figure show the use of high temperature (waste) heat from the power plant for the buildings; the figure at the right represents the use of waste heat, including cascading in temperature levels of the supply. The lower return temperature can lead to a more efficient process of electricity production.

3.3.4 Exergy smart storage

Especially renewables and free energy sources are not always available at the time they are required. Hence, when using renewable energy or waste flows, storage becomes more important in the design of a system. The most important exergy considerations when optimizing storage are:

e) When thermal energy is available at different temperature levels (i.e. exergy factors) the storage should be organised at these separate levels. Also stratified storage tanks make better use of the exergetic potential than mixed ones (see for example Torío 2012).

f) When considering a varying outdoor temperature, exergy can be 'created' in time when considering the reference environment to vary with time as well. For harvesting and preserving this 'free' exergy, storage systems are required. In practice this is what already happens in seasonal storage systems. This principle can be broadened by making use of the variation within the exergy factors in shorter periods of time by means of a heat pump, (e.g. 1 to 7 days, as discussed in chapters 3 and 4). The potential of this variation for 'creating exergy' by using storage is explored by Jansen (2013).

3.3.5 Use high-quality energy sources exergy efficiently

Apart from using low-quality heat sources for providing heating (i.e. matching the quality levels of demand and supply), also some processes that make use of high-quality energy input can be exergy efficient for heating purposes. In general the exergy efficiency of the system components should be looked at, rather than the energy efficiency. For the built environment the following conversion devices can in principle make smart use of the high quality input:

- A heat pump (which generates more heat or cold than the electricity input). Available heat pumps have exergetic efficiencies between 40 % and 60 % and possibly future research could develop heat pumps with even better performance.
- A cogeneration process (CHP) (combining the production of heat and power). In principle cogeneration can be exergy efficient and cost-effective (Bejan et al. 1996). However, this option will only be profitable if both heat and electricity outputs can be used (and preferably also if CO_2 emissions are used). The electricity production should be the main output, in order to have high exergy efficiency.

3.3.6 Avoid exergy destructive processes known to cause exergy losses

Many processes currently used are fundamentally 'flawed', since they inevitably destroy exergy (Bejan et al. 1996 and Szargut 2005). This means they cannot be thermodynamically improved and therefore should be avoided. Exergy destructive processes include:

- Combustion
- Resistance heating
- Mixing
- Throttling
- In general: all processes with large driving forces (e.g. large differences in temperature or pressure).

These inherently exergy destructive processes should be avoided or only applied for minor amount of energy flows. In this case the exergy destruction should be justified with reasons like costs, use of space or use of materials for example.

3.3.7 Avoid large chains of components

Every process involves exergy losses in order to take place, therefore large chains of components will lead to high exergy losses. Obviously, the best option depends on the available components and in some cases two good components perform better than one, but in general the fewer components and processes, the better.

3.4 Simplified exergy analysis: ten steps

In order to evaluate the exergy performance of potential energy systems and develop these into a draft design, a simplified exergy analysis should be performed. This way the overall exergy efficiency can be determined and, more importantly, insight in the losses per component and thereby the improvement possibilities can be obtained.

This section describes the following 10 steps in more detail:

1. Define the **system boundaries** of the project
2. Indicate the **reference temperature (T_{ref})**
3. Define the **system configuration** according to input = output approach
4. Determine **energy values** of all inputs and output
5. Determine the **exergy** of all inputs and outputs, (using the quality- or exergy factor of the energy)
6. **Display** exergy values in a clear way
7. **Analyse** losses
8. Propose **improvements** (to reduce losses)
9. **Repeat** step from step 4, until satisfied with results
10. **Present** final version including final performance (describing improvements and justifying remaining exergy losses)

The steps are further described below.

3.4.1 Step 1: Select the system boundaries for analysis

As discussed in section 3.1.5 the chosen system boundary has a large influence on the overall resulting exergy performance of the system. It should therefore be carefully selected and described in all analysis documents.

In the context of the Annex 64 a robust discussion has arisen around the need to have clear methods for setting system boundaries for analysis of community systems. In principle, for a complete analysis of how well we are using our resources, the complete energy chain from primary sources (referring to sources as they can be found in nature) to final demand has to be analysed. When the aim of an analysis is only to improve a certain part of a system, the system boundaries may enclose only a part of the entire chain.

For community scale systems the complete energy chain (starting with the primary sources and ending with the energy demand) is usually the most suitable. Various scenarios can be explored that use the same framework for the analyses, which enables direct comparison of alternatives. However, in some cases the physical boundaries of the urban area can also be used as the system boundary. This is for example suitable in case it is not yet clear where the energy inputs into the area will be coming from; in that case it can be wise to develop a system with the lowest exergy demand, since this will in principle be the easiest to supply.

Figure 7 provides an example of how the system boundary can shift interpretations. Considering system boundary 1, the system exergy efficiency will improve when low temperature heating and a low temperature district heating will be used. This means the entire system has the potential to have a better exergy performance. It does not mean that it does perform better than a higher temperature district heating system.

Considering system boundary 2, the effect on the entire system is evaluated. If the performance of the cogeneration does not increase as a result of the lower temperature demanded, there is no benefit and also no increase in exergy efficiency of the entire system.

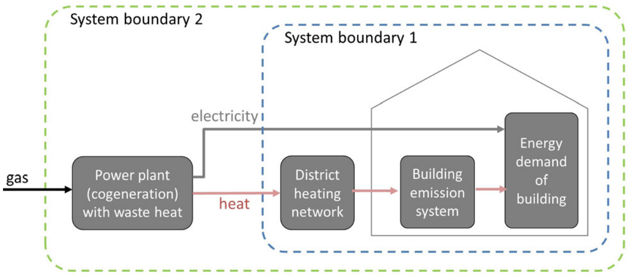


Figure 7 Comparison of two different system boundaries for a cogeneration system. (Jansen and Meggers 2016)

Summarizing, for system boundaries of exergy analysis one must consider:

- A system exergy efficiency is only meaningful when the system boundaries are clearly defined, particularly in case-studies.
- If only part of the energy chain is evaluated, exergy destruction can still increase outside of the chosen system boundary.
- Once the exergy factor of the input into a defined system boundary is changed, the upstream processes need to be considered. As long as the form of energy and the exergy factor of the system input is unaltered, an exergy optimization within the system boundaries is valid.
- It is possible to exclude a certain component from the system anlaysed, as long as this component is 'fixed', that is: if the componentn itself is not a topic of investigation.[1]
- **Hence, the system boundary preferably includes all components that are subject to investigation for the development of the system.**

3.4.2 Step 2: Select the reference environment

The definition and selection of the reference environment for the exergy analysis in buildings has always been a challenging issue, which deserves a special attention, as the considered reference environment strongly influences the results of the exergy analysis. As is the case with the system boundaries, the applied reference environment should always be clearly stated in all communications about an exergy assessment of any project.

The reference environment is considered as the ultimate sink of all energy interactions within the analysed system and must be in equilibrium with regard to its mechanical, thermal and chemical properties (Baehr 2005; Dincer and Rosen 2013). The concentration of different chemical elements in the atmospheric air is also regarded as homogeneous (Torío 2012; Torio and Schmidt 2011). Furthermore, the reference environment must not change as a result of energy and mass transfer with the system under consideration (Baehr 2005) and it must be available for use (Dincer and Rosen 2007). Based on these assumptions it can be concluded, that the properties of the outdoor air basically meet the requirement of the reference system and is therefore applicable for exergetic analysis.

As thoroughly discussed during the previous EBC Annex 49, it is in most cases recommended to use the variable outdoor air as the reference environment (Torio and Schmidt 2011).

Since the properties of investigated systems in the built environment are very close to those of the reference environment, the exergy analysis shows high sensitivity regarding changing conditions of the reference environment (Torio and Schmidt 2011). Therefore it is also recommended to use dynamic simulations and the varying outdoor temperature. Especially for cooling this is essential, since cooling in many mild climates only occurs some hours per day. If a monthly or even daily mean temperature would be used, this would result in a negative exergy demand since the (monthly or daily) average outdoor temperature in mild climates is usually below the maximum allowed indoor temperature. The cooling however also occurs when outdoor temperature is above indoor temperature. In the Annex 49 guidebook (Torío and Schmidt 2011) and Jansen (2013) the difference between two cooling modes is explained: cooling when outdoor temperature is below indoor temperature and cooling when outdoor temperature is above maximum allowed indoor temperature. Only in the latter in fact represents an exergy demand: the first cooling situation actually could theoretically produce work and thus contains exergy.

Hence, for exergy analysis of cooling it is necessary to perform dynamic simulations using the varying outdoor temperature.

3.4.3 Step 3: Define the system components according to input = output approach

In order to determine the exergy losses occurring in each energy component of process step, the system must be simplified into a chain of components according to an input=output approach. This approach was developed by Schmidt (2004) and means that the output of system component x must be equal to the input of the next system component. This way there can be no exergy losses between components; all losses are 'assigned' to one component.

To define the system, one has to:

- Start with the demand
- Design a configuration (= combination of energy

[1] The last bullet point can be explained with the following example: If an existing field of solar collectors will be used in a community energy system, and only the system needs to be developed and the solar field is considered as given, it is possible to start with the output of the solar collector field. However, if there is no solar collector field yet and it could for example also be designed as solar panel (PV) field, the system boundary needs to shift one step up the energy chain and the solar radiation should be considered as the first input.

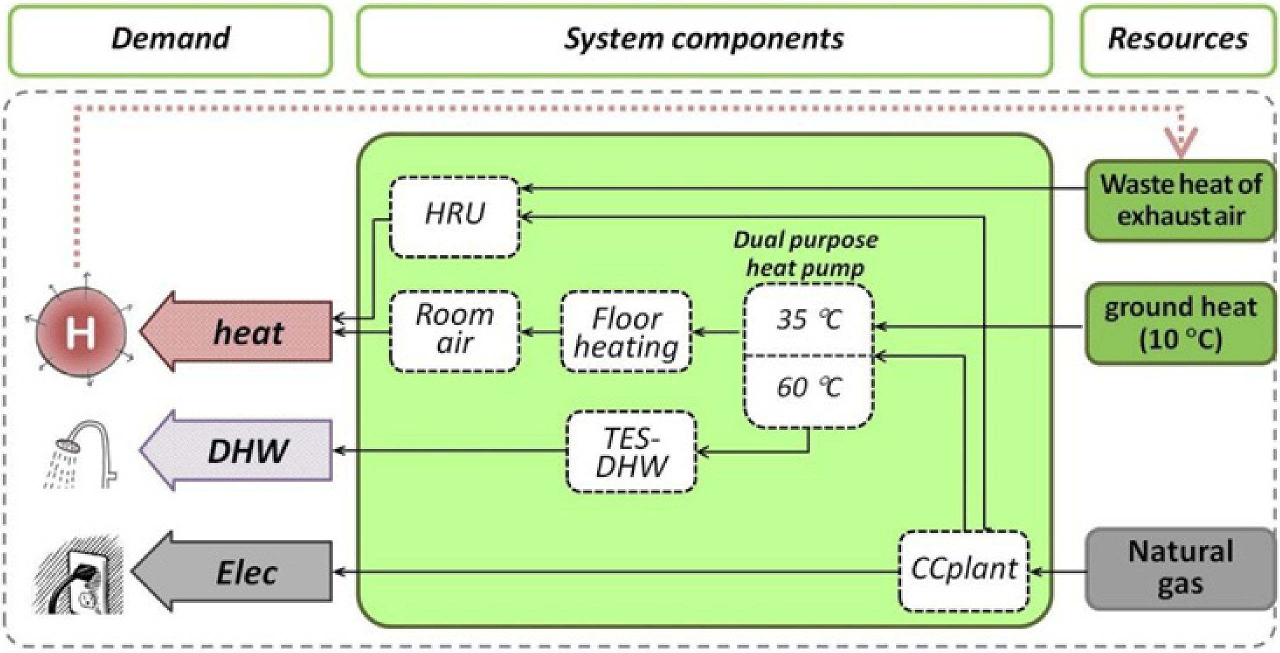


Figure 8 Simplified scheme of energy system configuration, where components can have more than one connection to other components. This scheme represents a simple domestic system for space heating and hot water production using a dual purpose heat pump. (from Jansen 2013).

system components that are able to supply the demand), where the exergy input of the demand is equal to the exergy output of the next component

- Add a 'room air' component when aiming to analyse the losses between emission system (for example radiator) and space heating demand. This exergy loss occurs due to a temperature difference (Schmidt 2004)

The energy chain shown in Figure 3 is set up according to the input output approach. In this visualisation only one output of each component is considered, leading to a linear configuration.

Figure 8 shows an example of an energy configuration where more than one output of energy components is included, leading to more interconnections between components. This slightly more complex system makes the visualisations of exergy losses slightly more complex as well, as will be explained at step 6.

3.4.4 Step 4: Determine energy values of all inputs and output

As a first step all energy values of all inputs (and thereby outputs) need to be determined. As a start the energy demand needs to be calculated. This can be done using common software tools, such as EnergyPlus or DesignBuilder, or by nationally defined calculation tools.

Following, all energy flows results from the required output plus the energy losses within the system component. The same can be achieved by dividing the output by the energy efficiency of the system component. The energy input can consist of different forms of energy: mainly heat, electricity or fuel. This is shown in Figure 9.

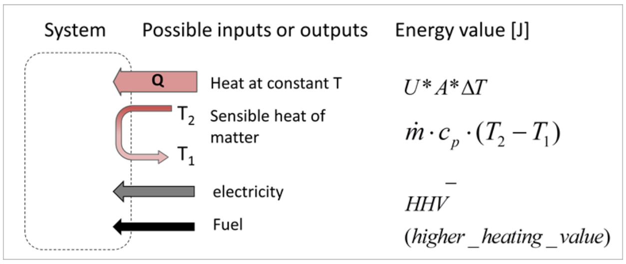


Figure 9 Energy concent of different energy inputs (heat at constant T, heat related to massflow,electricity and fuels).

3.4.5 Step 5: Determine the exergy of all inputs and outputs, (using the exergy factor)

After the calculation of the energy values, the exergy values can be relatively easily determined by multiplying the energy value with the exergy factor (Fq or fex) of the related form of energy and in case of heat, the temperature, according to equation 5.

$$Exergy = Energy \cdot F_q \qquad \text{Equation 5}$$

In Figure 10, the quality factors or exergy factors of the most common forms of energy are shown. Special attention should be paid to the exergy factor of heat that is supplied by a medium (for example water or air) of which the temperature changes as a results of the heat transfer. In this case - assuming a constant

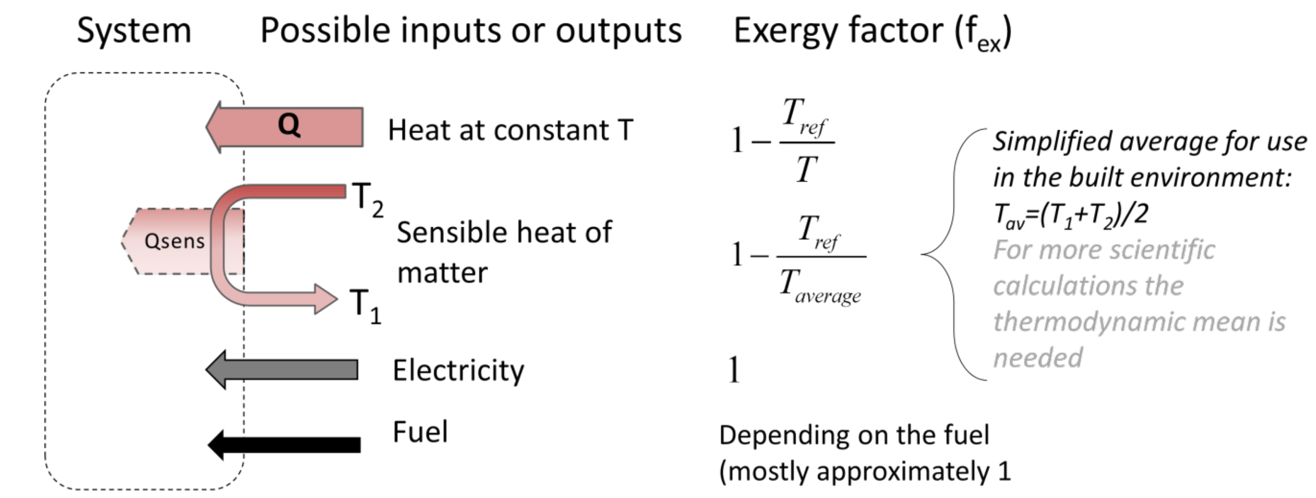


Figure 10 Exergy factor of different forms of energy (Jansen 2015).

heat capacity of the medium - the logarithmic mean temperature should be used (see equation 3) (Kallert 2018). However, it has been shown that for application in the built environment, with relatively small temperature difference, the simple mean temperature can also be used without significant effect on the results (Jansen 2015).

3.4.6 Step 6: Display energy and exergy values in a clear way

In order to enable an easy analysis of the losses, the energy and exergy values should be clearly visualised. The energy and exergy values can be displayed in three ways:

1. Exergy flow diagram (see Figure 11).
   This is applicable for systems with a relatively simple configuration with all components in a row, such as the one shown in Figure 3.
2. Exergy losses chart (see Figure 12)
   This way of presenting the losses is possible for any system: it shows the exergy losses in each component, but the relation between components is less clear.
3. Sankey diagram with exergy values. (see Figure 13)
   This way both the losses and the relation between components can be visualised at the same time.

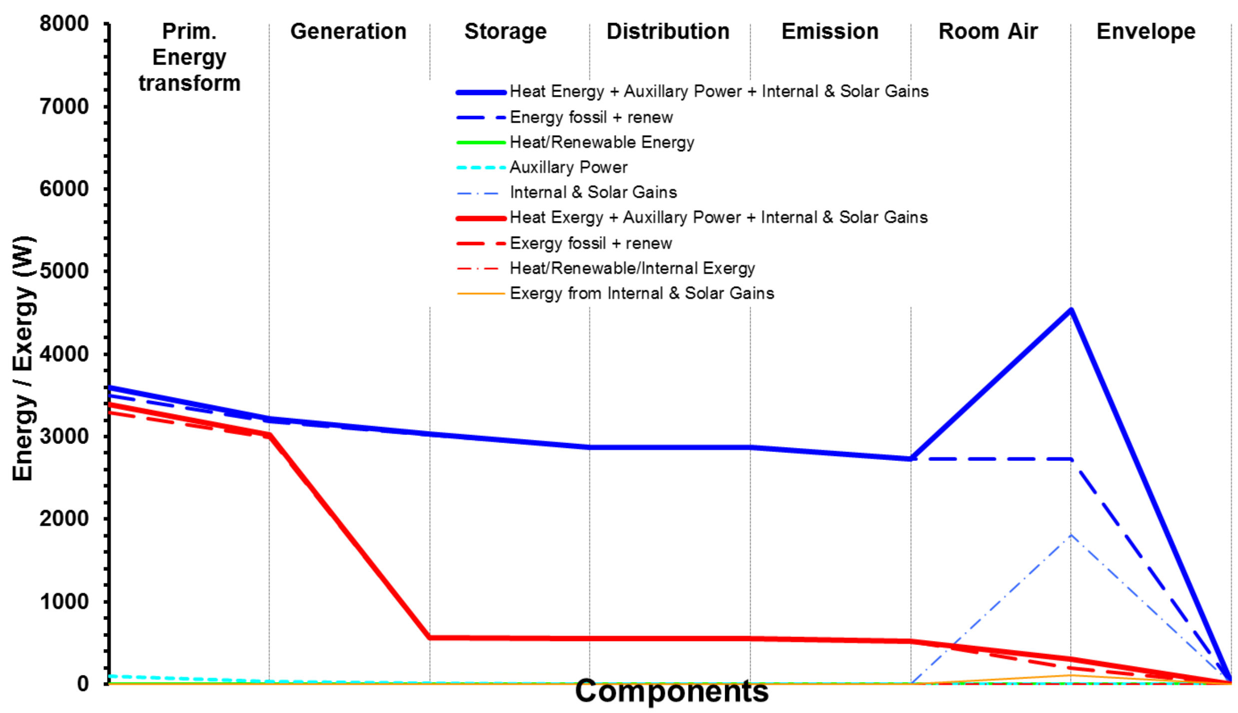


Figure 11 Example of visualisation option 1: Exergy flow diagram. It shows the energy and exergy flows in each sub-component of the energy supply chain (taken from the exergy pre-design tool of Annex 49. www.annex49.com). In this particular example a condensing boiler is selected as heat generation technology; this is clearly visible due to the small losses according to an energy approach (the blue line) and the significant losses according to the exergy analysys (the red line)

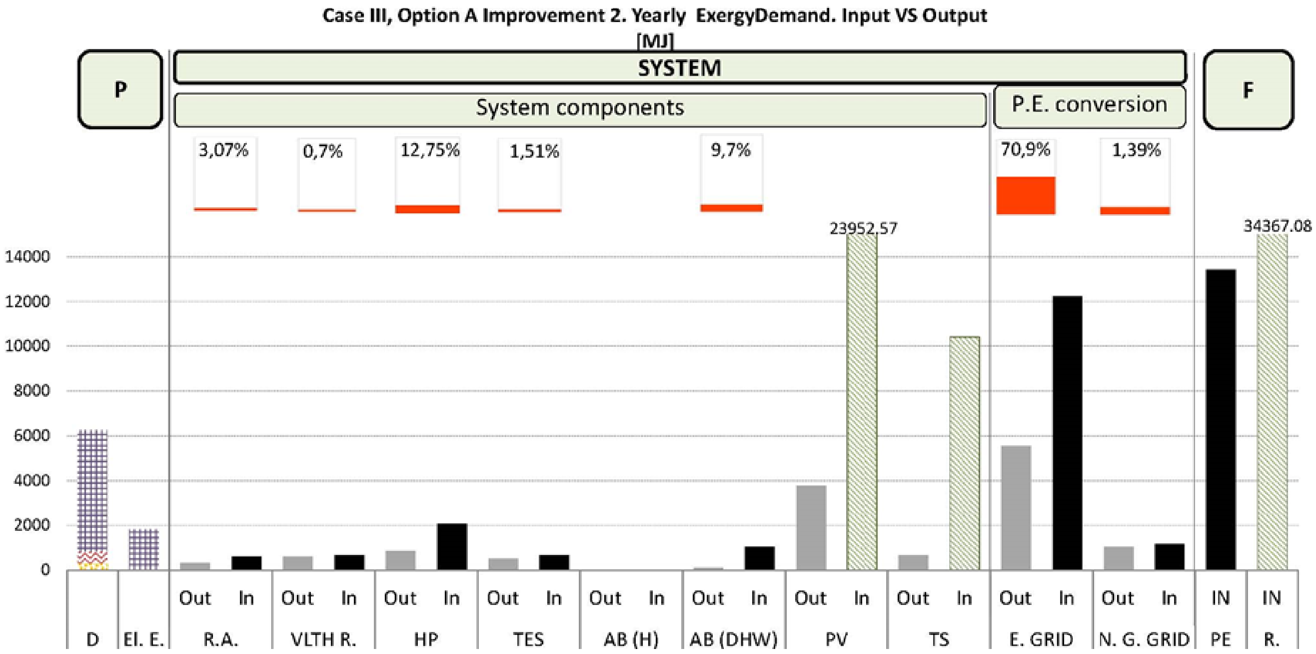


Figure 12 Example of visualisation option 2: Exergy losses chart. It shows the annual exergy input and output of each sub-component, as well as the type fo energy involved. (Teres-Zubiaga et al. 2013).

List of abbreviations of the system components: D: Demand; El.E: Electricity exported; R.A.: Room Air; VLTH.R: Very low temrpature heating radiator; HP: Heat Pump; TES:Thermal Energy Storage; AB(H): Auxiliary Boiler for heating; AB(DHW); aixiliary boiler for hot water; PV: Photo Voltaics; TS: Thermal Solar; E.GRID: Electricity from the grid; N.G.Grid; natural gas from the grid; PE: primary energy (fossil);R: renewable energy input.

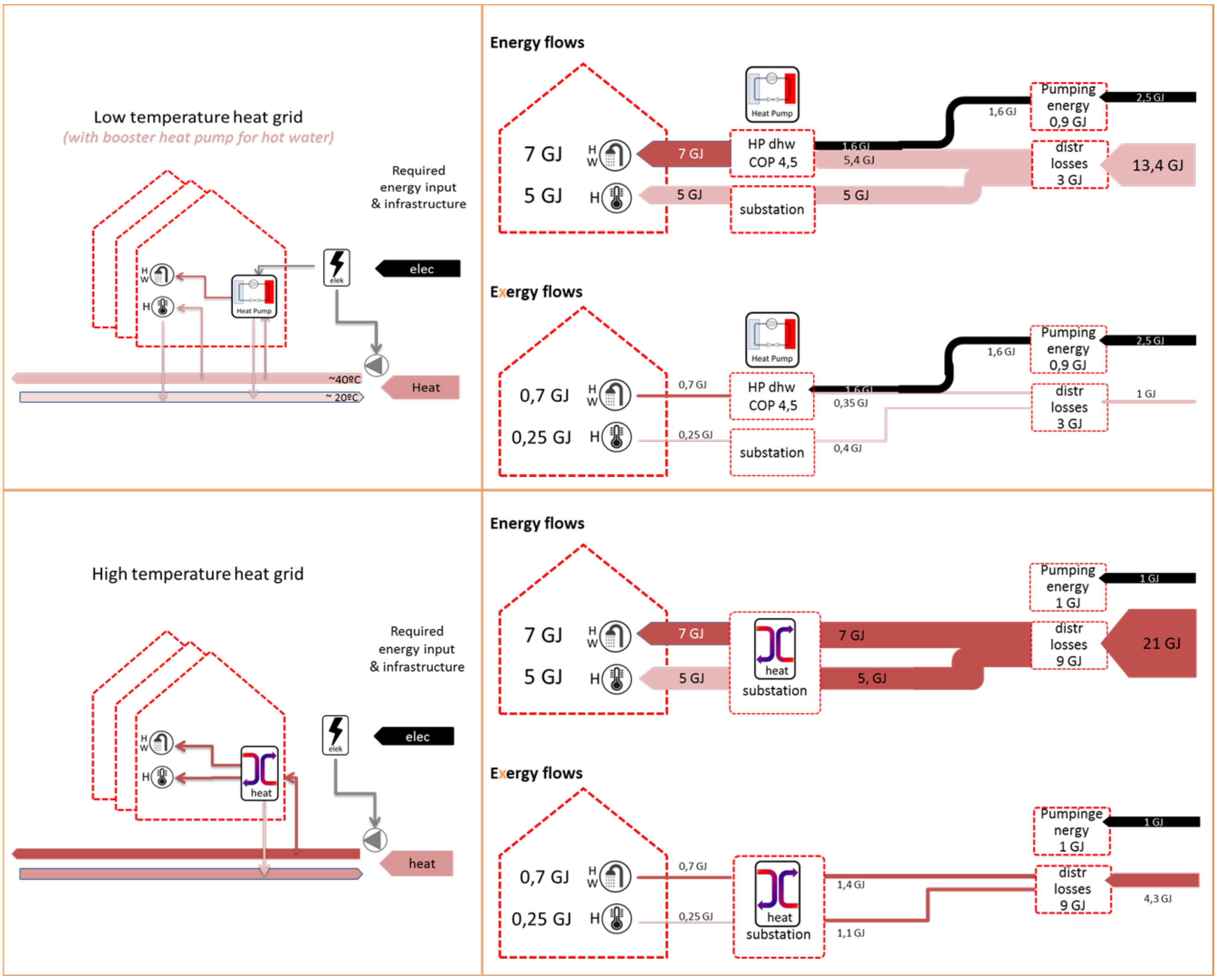


Figure 13 Visualisation of exergy flows and exergy losses as sankey diagram (Jansen 2017).

3.4.7 Step 7: Analyse exergy losses

Once the losses are identified and quantified, possibilities to reduce these losses can be investigated. Finding solutions to reduce losses is a creative process which starts with the identification of the losses as presented in step 6. Furthermore, the exergy principles presented in section 3.3 can be applied for further improvement.

For a structured analysis of the losses the following question can be helpful to explore potential solutions: What is causing the losses (avoidable/unavoidable losses (Tsatsaronis and Park 2002))? Usually it is caused by one of the following reasons:

1. A mismatch in temperature
2. Poor component properties (e.g. a heat pump with a COP much lower than COP_{Carnot})
3. A fundamentally flawed process (e.g. combustion)

At the following step the related solutions are presented.

3.4.8 Step 8: Propose improvements to reduce the losses

In relation to the previous step the solutions can be considered as given in Table 1.

3.4.9 Step 9: Repeat step from step 4, until satisfied with the results

For the new, improved energy system the steps 3 until 8 can be repeated until the results are satisfying and all exergy losses are justified with other reasons, like costs.

3.4.10 Step 10: Present final version including improvements

The final version can be presented, showing the system configuration (from step 3) as well as the energy and exergy flows as visualised at step 7.
For all significant losses a justification based on other indicators (CO_2, costs, maintenance, etc.) can be given.

3.5 Summary and conclusions on exergy thinking

This chapter presented the outcome of the research work on exergy thinking and the relation between exergy and other (sustainability) indicators. Although there is no common agreement between everyone involved in exergy analysis, it is proposed to use the thermodynamic definition of exergy as a separate indicator to get insight into how well we are using our resources. The aim of an exergy analysis and of the concept of designing LowEx communities is to minimize the exergy losses as much as possible and as much as reasonable.

Table 1 Presentation of causes for exergy losses in systems and potential solutions

What is causing the losses?	Potential solution
1. A mismatch in temperature	• Is it possible to reduce the temperature difference? • Are other sources with a matching temperature available?
2. Poor component properties (e.g. a heat pump with a COP much lower than COP_{Carnot})	• Is the same type of component available with better - more exergy efficient – properties?
3. A fundamentally flawed process (e.g. combustion)	• Can the employment of this component be further reduced by transferring (part of) the output to another component?

NOTE: Always take into account how the change of one component influences losses in other components. Sometimes reducing losses in one will increase the exergy losses in the next component.

It was also shown that other criteria such as renewability, storability or costs can best be regarded separately in addition to the exergy values. This way insight from exergy analysis is gained, while additional reasons for choosing one system over another are added. This means sometimes exergy losses can be admitted, as long as they are justified by other reasons.

Furthermore, several approaches are presented on how to use the exergy concept in different phases of the design process for sustainable energy communities: using with exergy principles in the early design and performing (simplified) exergy analyses for further improving the energy system. For the last phase of detailed design and optimization different tools can be used, which will be described in chapter 6.

Furthermore, recommendations on the utilisation of the LowEx approach are given and summarised in a easy to follow "ten steps for a simplified exergy analysis in communities".

4 LowEx supply technologies

A well-designed energy system is the main basis for the exergy efficient supply of buildings and communities. Hence, concepts and technologies allowing a flexible supply of different demands with maximal share of low-valued local and renewable energy sources are identified and described as part of this chapter.

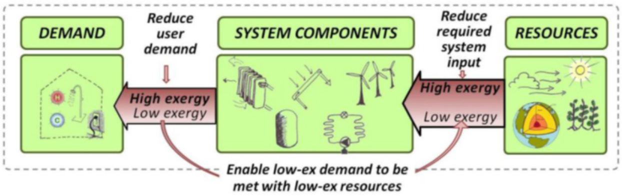


Figure 14 The exergy supply chain. Scheme of energy systems for the built environment: the exergy approach can support systems where the low exergy demand can be met with low exergy resources (Jansen 2013).

The technological considerations include both demand- and supply-side aspects. As part of chapter 4.1 the requirements for efficient buildings and user behaviour are discussed. In the course of chapter 4.2 on "decentralized supply solutions and storage technologies", which serve as interfaces for municipal supply, different options are compared. Descriptions of different supply technologies (e.g. heat pumps or solar thermal collectors) are found in chapter 4.3

4.1 Building typologies and demand

Building properties mainly determine the seasonal pattern of the energy demand profile. Here are involved the outdoor climate zone, size of the neighbourhood or district, size of the building, grade of insulation and HVAC-systems properties as main influencing factors.

An energy community is defined as a cluster of buildings in which every building can generate both electricity and heat using micro-generation technologies, such as CHP systems or photovoltaic panels and heat pumps, and can share both types of energy with the other buildings. The expected advantages are such as that of energy sharing among buildings, i.e. the extent to which energy sharing can minimise the energy input to the boundary or the amount of local energy production and consumption that is possible. Shifting demands for energy and the existing energy supply can lead to either surplus or deficient amounts of energy at various hours of the day depending on variations in the demand profile. These surpluses and deficits can also be shared with neighbouring buildings.

4.1.1 Energy community and Zero Energy Building

The key motivation behind the Zero Energy Building (ZEB) concept is to utilise distributed energy resources and energy efficiency in energy systems in the building. To increase energy efficiency even more, energy challenges focus not only on a single building but also on a group of buildings that might have the possibility to reach a closer look to zero energy situation, a so-called 'energy community' or 'energy district'. Moreover, ZEB actions are making high efficient energy systems at the energy demand side. This trend leads that local energy system integrations and energy sharing have potentials to raise/improve energy efficiency at the demand side. These are the important suggestions that decentralized energy systems can take a significant role in future energy supply (Kayo et al. 2014; Kayo et al. 2016; Kayo and Suzuki 2016).

Figure 15 shows the energy demands of electricity and heat of different building types (Shase 2003). The data consist of the demand distribution for every month and the average hourly demand for representative days in each month. The variety and differences among different buildings in different times or seasons make it possible to share energy among a group of buildings and raise energy sufficiency.

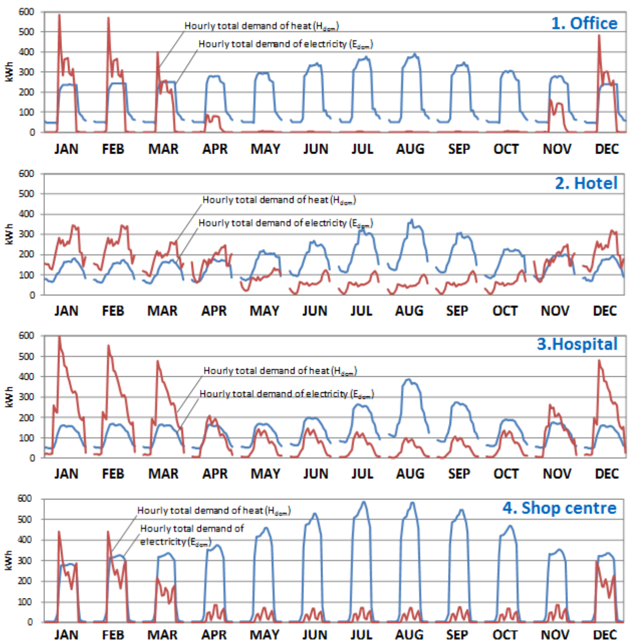


Figure 15 Demand profiles for heat and electricity of different building types (Shase 2003).

Energy infrastructures as district heating grids can be used more efficiently by utilising the differences in demand profiles. The integration of a larger group of buildings and users into a system helps to level out peak demands and reduce the simultaneous use of energy. Furthermore, concepts like cascading (see 5.3.10) can be applied to achieve a more exergy adapted supply solution.

4.1.2 Occupant behaviour (energy demand profiles)

When analysing community heating systems, not only the characteristics of the supply system or the buildings but also the occupant behaviour especially in residential buildings can have a major impact on the energy demand. In particular in the early stage of planning, when measured data is not available, prediction of user behaviour using randomized user profiles offers prospects for accurate analysis. For detailed holistic energy analysis of district heating systems using (randomized) user profiles the following aspects are of major importance:

- How many residents are at home at which time?
- How many of those residents are active at which time, meaning not asleep?
- When is electricity demand caused by appliances?
- When is thermal energy needed?
- How much DHW used?

For the analysis of complex energy systems, such as community supply systems, all aspects need to be considered simultaneously since they are influencing each other and have significant influences on energy demand as well (Kallert 2018).

In the course of the Annex 64 project, two profile generators are presented by the participants, which allow creating demand profiles depending on user behaviour.

"ProfileMaker2.x" – Predicting User Behaviour

The software tool "ProfileMaker2.x" (see also methods and tools section 6.1.14) allows the creation of stochastic user profiles for application in thermal building simulation. The tool generates profiles of the presence and activity of the inhabitants as well as electricity and DHW profiles automatically. Figure 16 shows the main principle for creating randomized user profiles.

In a first step a randomized profile for "occupancy" is created by taking the following possibilities into account: "inactive" (sleeping), "active" (e.g. housework, watching TV or reading) and "not at home". This profile is used for calculating the body heat emitted to the thermal zone, the DHW demand and the power demand (e.g. electricity used for appliances and lighting). Simultaneously the internal gains are calculated. Parameters, such as the number of occupants, time of day and weather data, are considered while preparing the profiles. Next to the profiles the classification of three different user types (classes) is possible: "average", "saver" and "waster" are implemented. "Average" and "saver" are equipped with night setback, which means that the room temperature is lowered by 3 °C for seven hours during the night. For each user type the number of inhabitants can be varied in order to reflect a two-person household as well as a family of four or five at the same time. Similarly, these assumptions can be further used to re-

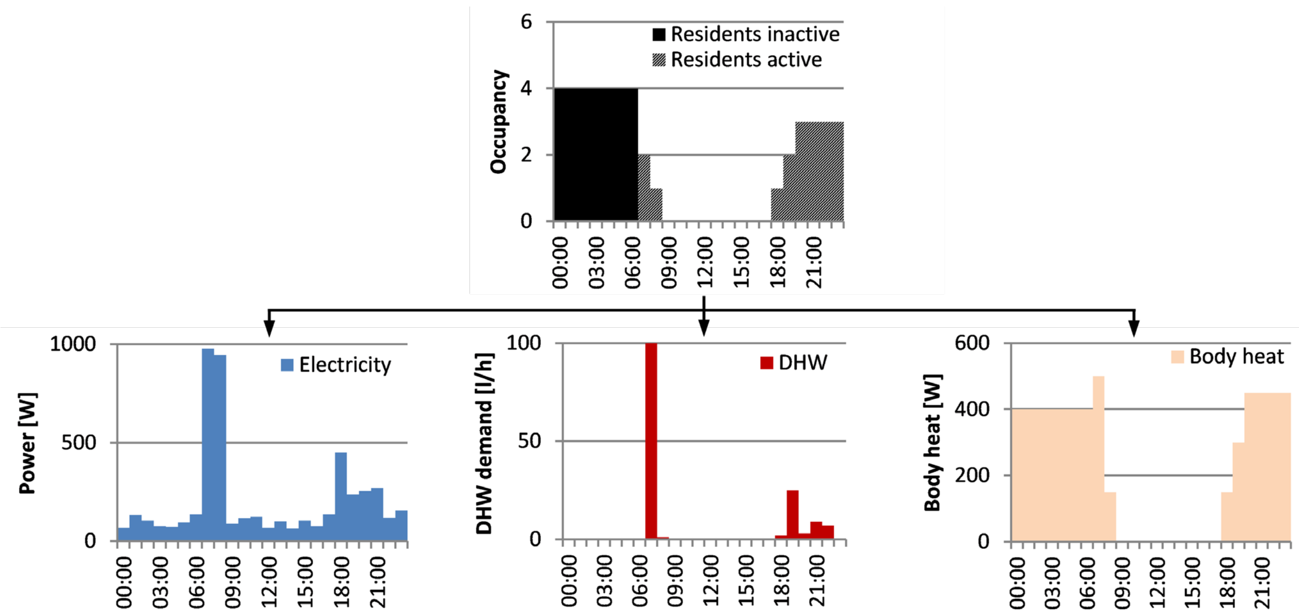


Figure 16 Example occupancy profile and resulting profiles (Power, DHW and Body heat) for a random day (Kallert 2018).

present a certain group of society (e.g. a young couple without children, retired couples or a single person present all day). Next to the profiles and user classification, which mainly influences the space heating demand, different DHW profiles representing different draw-off events are implemented. The routines of the VBA tool are connected to "number of inhabitants" as well as "occupancy" in order to avoid logical errors. The resolution of the profiles is on an hourly basis and profiles with a length ranging from one to 365 days can be generated. It is distinguished in day of the year as well as week day and weekend. Since the tool has been designed for generating user profiles for small scale district heating grids a simultaneity factor is determined if the number of buildings is higher than two.

An example for heating demand for space heating and domestic hot water in a micro district heating grid which consist of 10 new buildings is shown in Figure 17. The simulation is carried out for a random day (February 2nd (week day)). The variation of space heating demand depending on the type of selected user profile is represented by the orange lines. The variation of DHW demand is represented by the blue lines. The outdoor temperature is represented by the red dashed lines.

"OLEC-energy profile generator" (heating, domestic hot water) for districts

The OLEC profile generator is based on the aggregated building approach (Willems and Claessen 2017). The Octave calculation core, which is semi-dynamic (time step is adjustable), is a further development of the "Two mass model", is described in (Koene et al. 2004):

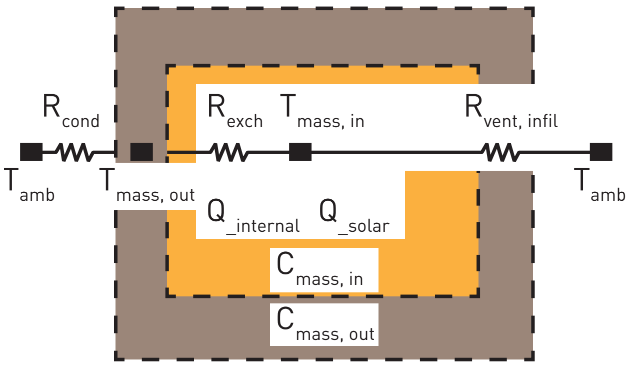


Figure 18 Graphical representation of the two mass model [Koene et al. 2004] used here to model the dynamic behaviour of a building in thermal processes.

For the presence of the occupants in residential buildings the schemes of (Aerts et al. 2014) are used.

Figure 19 shows the 7 options to choose user profiles.

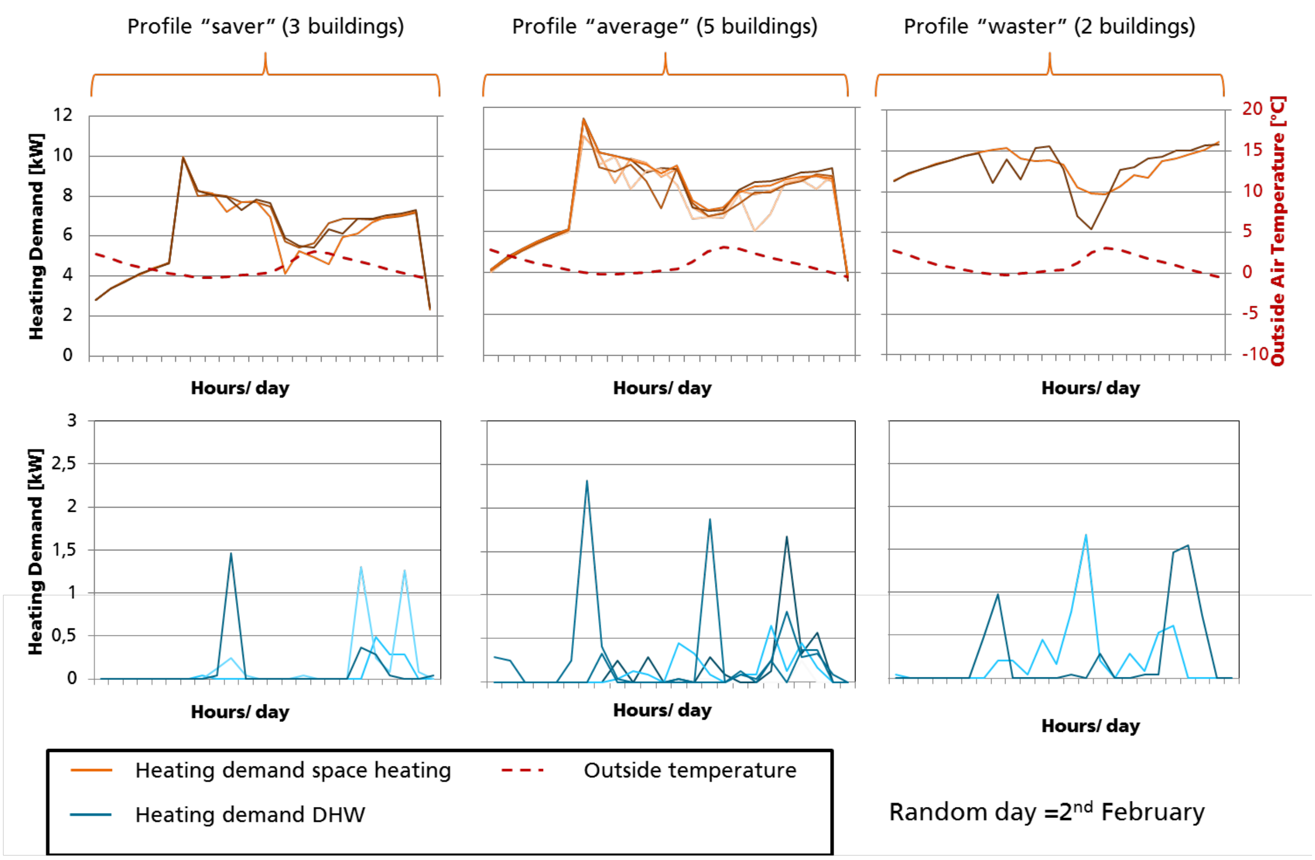


Figure 17 Examples for heating demand (space heating and PWH respectively DHW) for a random day (February 2nd) (Kallert 2018).

For the internal heat production by persons, appliances and lighting the plan of approach LTGO (van Rijn et al. 1999), is used with an internal heat intensity for persons, appliances and lighting. For internal heat load outdoor operating times is in the basic use of the national standard of the Netherlands NEN-EN-ISO 13790.

Depending on the intensity of the occupation also the ventilation flow rate is changing according to the specified type of ventilation control. In Figure 20 some examples are shown of heating demand profiles of dwellings on a hourly basis.

Figure 21 shows the variations in the yearly energy profiles for various user profiles.

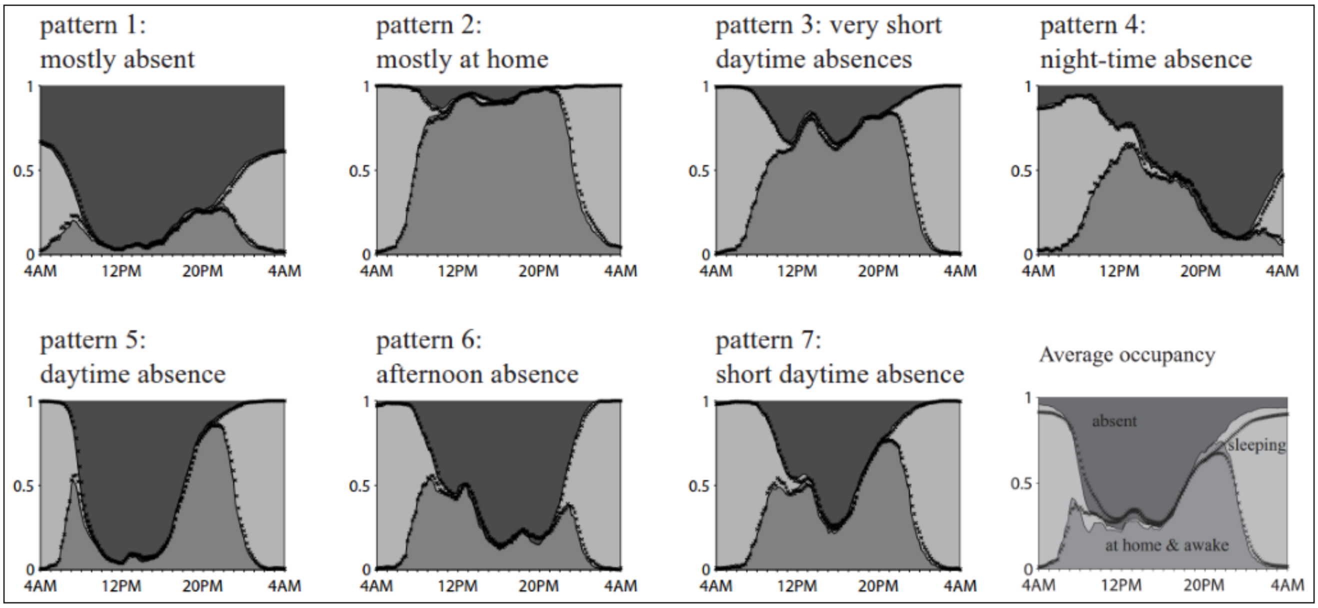


Figure 19 The 7 user profiles from the research of Aerts (Aerts et al. 2014).

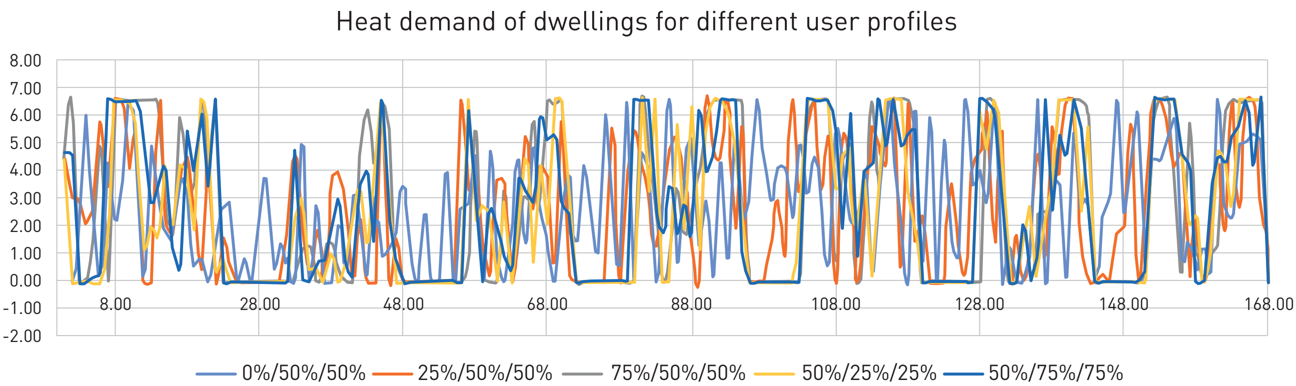


Figure 20 Examples of hourly heating demand profiles in dwellings

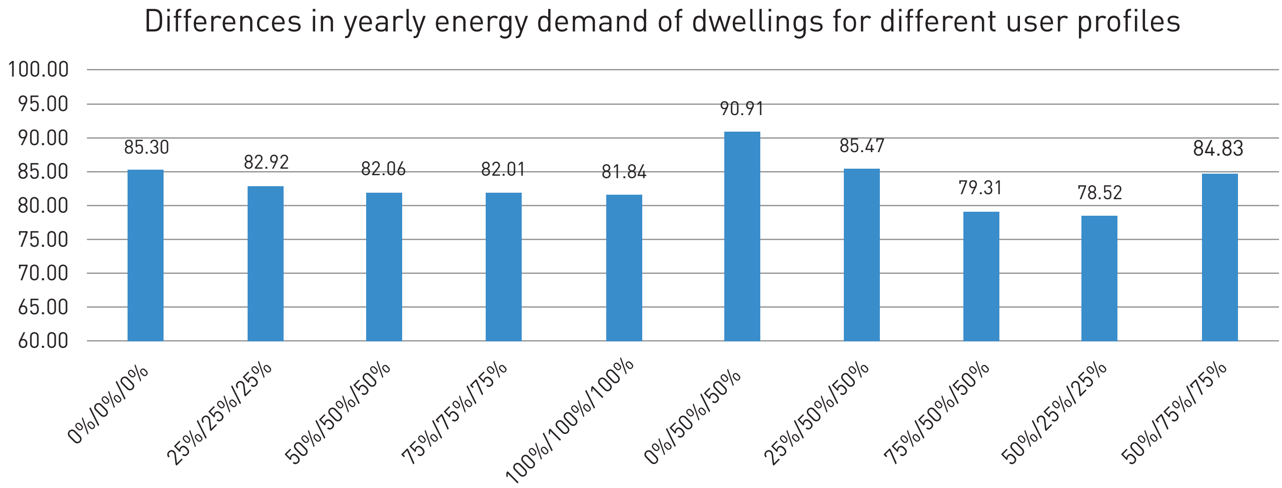


Figure 21 Differences in yearly energy demand of dwellings for different user profiles

4.1.3 Control approaches

One of the influencing factors of the exergy demand of district energy systems is the control and operation strategy. Energy infrastructures, as e.g. a fourth Generation District Heating (4GDH) [Gong and Werner 2015, Lund et al. 2014] system, can only function properly, if the connected buildings can operate at relatively low supply temperatures. The prerequisites are suitable heat emission systems such as floor heating but also suitable control strategies, as the following explanation shows.

Building energy systems can be considered as "systems of systems" (SoS), being composed of interacting subsystems that require suitable control approaches in order to achieve a high energy conversion efficiency. The energy demand of a building has a lower bound resulting from the thermal comfort and air quality constraints. Exergy-based control strategies aim to fulfill the constraints while minimizing the sum of exergy destruction and loss (Razmara et al. 2015). If buildings interact via electrical or thermal grids, they become systems in a larger SoS. This connection offers flexibility for applying approaches such as demand side management (Schild et al. 2015). Uno and Shimoda (2012) present an approach for cooperative management aimed at saving energy. Moreover, exergy-based control approaches can be extended to district energy systems (see also case study in section 5.2.1).

If each building in such a district energy system is controlled to minimize the sum of exergy destruction and loss and communicates the required supply temperature, there are two positive effects: the exergy demand of all consumers can be reduced and the energy conversion efficiency of the entire district network can be increased. For example, in a heating network supplied by a heat pump, the flow temperature set point can be determined by the consumer that requires the highest supply temperature. This leads to a higher COP of the heat pump and consequently a lower exergy destruction.

Consequently, the control strategies of the single buildings and the district energy system influence each other and should be matched in order to achieve the minimum exergy demand of the entire district.

In addition the grid needs a control to minimize the losses. The grid is concerning the demand of the buildings and also the supply of heat and applied storage. In the short term, local heat storage on building level can change the energy profile to the grid. But the seasonal storage (underground or in large district heating storage tanks) introduces time constants of month of even seasons. These controls concerning storage need to apply a sort of predicting control to manage expected exergy losses and energy use and actual available stored energy. Automated algorithms are not generally developed. In most cases the optimization is done manually, as in the Princeton Campus cooling facility (see 5.3.2 and 5.3.14). Development will strongly depend on the boundary conditions and aims of the control.

4.2 Interface of demand and source – examples for centralised and decentralised community supply

As part of the EBC Annex 64 centralized supply concepts that are using a heating grid and decentralised supply concepts and technologies are discussed. Decentralized or distributed systems are stand-alone systems that supply space heating and domestic hot water and are not connected to a heat distribution system. The decentralized systems only supply one building with one or more accommodation units. The building is not connected to a central heat distribution infrastructure. On the contrary heat supply systems are district heat supply schemes, which allow the supply of small neighbourhoods to large cities.

4.2.1 District heating supply schemes

A district heating (DH) system is based on a heat distribution infrastructure, the heat network (municipal heat supply). The evolution of district heating has gone through three generations which are characterized by the type of transport media and the network temperature levels. The 1st generation DH system is steam-based system, which includes a large diameter steam supply pipe and a small diameter condensing pipe to return condensed water. The 2nd generation DH uses pressurized hot water as transporting media to supply temperature above 100 °C. Pipes were insulated onsite and substations were built onsite. The 3rd generation DH was introduced in 1970s. It represents medium network supply temperature between 80 °C to 100 °C. The DH pipes in the 3rd generation network use pre-fabricated, pre-insulated metal pipes directly buried in the ground with a certain distance between the centre of the pipe to the ground surface and substations became factory assembled and insulated (Frederiksen et al. 2013).

Today, the 4th generation DH (4GDH) is emerging as a new system to replace the existing 3rd generation DH system. 4GDH is also named as low temperature district heating (LTDH). LTDH has been continuously

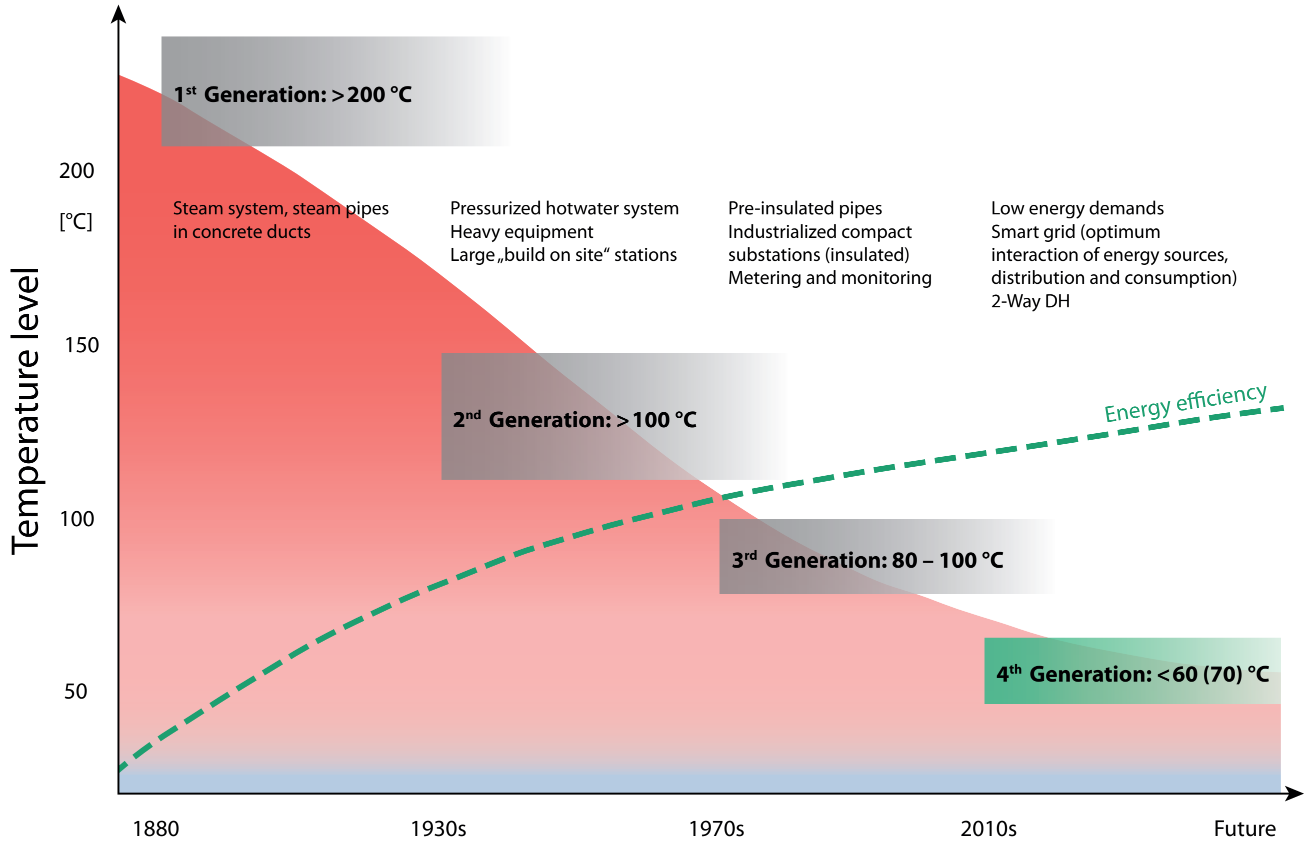


Figure 22 Illustration of the concept of 4th Generation District Heating in comparison to the previous three generations (Schmidt and Kallert 2017).

developed as the next generation DH ready to replace the current medium temperature DH system. LTDH based on renewable energy can substantially reduce total greenhouse gas emissions and secure energy supply for future development of society (Lund et al. 2014). It has the ability to supply low-temperature DH for space heating and domestic hot water for various types of buildings, to distribute heat with low heat losses and ability to recycle heat from low-temperature waste heat and renewable energy sources. From various research and development of LTDH projects, it has been shown that it is both technically feasible and economically sound to change current high/medium temperature district heating system to LTDH for both new and existing building areas (Rosa et al. 2014).

The required temperature in the low-temperature district heating system can be supplied with most current heating supply technologies including both conventional CHP plants with boilers and renewable energy based solar heating and geothermal heating. However, on a community level there are various heat sources available which have a temperature level below the minimum supply temperature required in the low-temperature district heating. Such heat sources can be sewage water, waste heat recovered from server centre or electric transformer, or shallow geothermal heat (Li et al. 2017). These heat sources can be exploited by ultra-low temperature district heating. Ultra-Low Temperature District Heating (U-LT-DH) are networks that have supply temperature below 50 °C and use temperature booster units to boost the supply temperature to sufficient levels to allow instantaneous DHW preparation (Gudmundsson et al. 2014). From both theoretical and practical point of view, ultra-low temperature district heating can diversify the heat sources, fully utilize local available waste heat, and increase the flexibility of the decentralized heat supply, thus achieve sustainable development for the community.

Significance of district heating in the context of a demand-adapted community supply
LTDH has benefits in both heat distribution and heat generation. In the heat distribution, it reduces the network heat loss and improves quality match between heat supply and heat demand. In the heat generation, lower network supply and return temperature helps to improve CHP plant power to heat ratio and recover waste heat through flue gas condensation, achieves higher COP values for heat pump and enlarges the utilization of low-temperature waste heat and renewable energy.

In general heating networks should not be understood as a "technology solution". It is a "system solution" which is mainly characterized by the supplying technologies, the characteristics of the buildings respectively the customers and the network parameters (Kallert 2018). Approaches for evaluation are e.g. found in (Schmidt and Kallert 2017; Kallert et al. 2017). As part of this work the potential benefits to improve performance in low-temperature district heating networks when using an exergy approach are demonstrated.

4.2.2 Cascading heat utilization in building clusters

In (Koefinger, 2016) the importance and the various advantages of reducing operation temperatures in district heating networks were discussed. In recent years, due to the uncertain price development of fossil fuels, combined with the close link to the electricity market (especially for cogeneration plants falling electricity prices are problematic), the profitability of many traditional district heating networks has significantly been reduced. The integration of alternative heat sources such as solar thermal, geothermal or ambient heat and industrial waste heat into district heating networks is in many cases difficult due to low temperature (LT) levels and fluctuating availability. A significant reduction of temperatures in heating networks, both in the supply and in return line is a key action to a transition to the next, the so called 4th generation of district heating.

Substantial benefits of reduced system temperatures are:

1. A significant increase of the potential to integrate renewable heat sources
2. In extraction condensing turbines, the efficiency increases and in extraction-back-pressure thermal power plants the share of generated electricity increases.
3. With a constant power input, the mass flow decreases in the network and this reduces the pumping costs. At the same mass flow, the network capacity can be increased (enabling the connection of new consumers). Thus the transport lines can have smaller dimensions, resulting in lower investment costs.
4. Reduced heat losses due to the lower temperature difference to the surrounding soil.

The temperatures in a district heating network are determined by the connected consumers. So the return temperatures result mainly from the cooling of the heat carrier in the buildings heating system and the properties of the substations. However, the return temperatures show a slight upward trend with increasing heat demand, resulting from the mass flow control in the buildings and any existing bypasses between the supply and return line in the grid.

The supply temperatures are determined on the one hand by domestic hot water preparation requirements (especially in summer) and the design of heating systems, on the other hand by the amount of transferred heat (especially in winter). As the difference between supply and return temperature (ΔT) in case of an increasing heat demand is adjusted linearly, the supply is directly dependent from the return temperatures (at most times in the year). Accordingly, a reduction of the consumer side return temperatures is an essential measure to also reduce the supply temperatures. A reduction of the system temperatures allows a better integration of renewable sources into the district heating network. Considering that the supply and return temperatures are linearly dependent, such a reduction is possible by heat-cascade solutions, as illustrated in Figure 23.

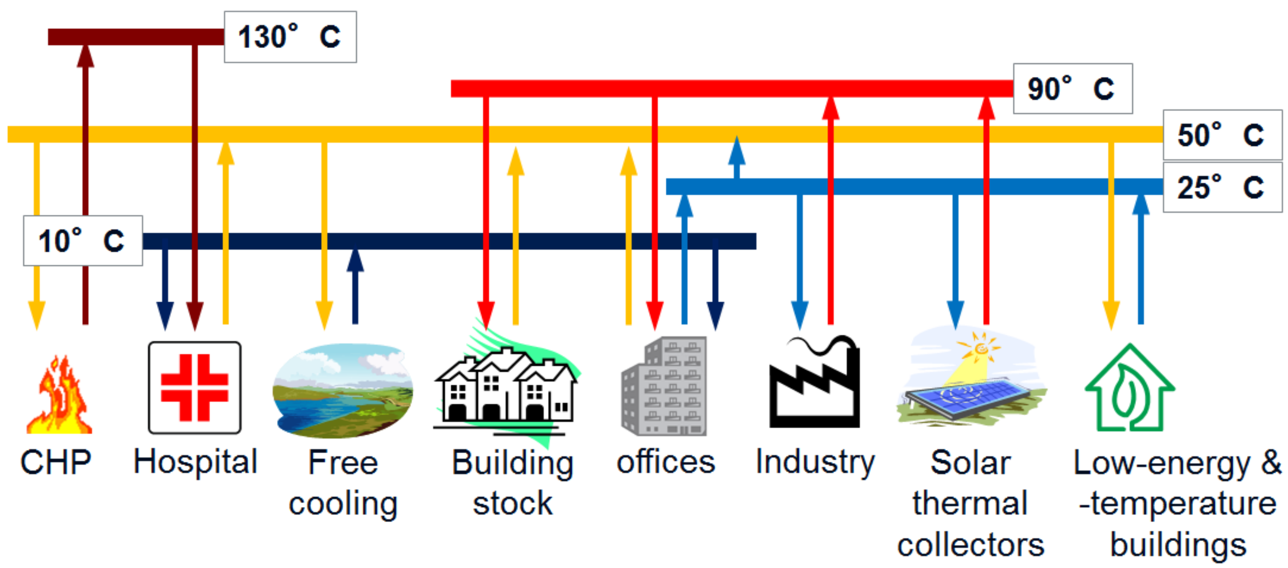


Figure 23 Examples of heat cascades between producers and consumers with different temperature requirements.

As part of (Koefinger, 2016) it was aimed to analyse potentials and to develop and evaluate concepts for the reduction of local return temperatures in urban district heating systems by implementing energy-cascades between buildings, e.g. using the return flow of high-temperature consumers (HTC) as supply flow for low-temperature consumers (LTC). Therefore optimization potentials are identified in characteristic building clusters, considering the influence of these measures on the momentary and the average return temperatures and mass flow rates. Different cascading options were tested. Using the return of HTC as supply for LTC can be done either indirectly through the return line of the network or directly through an interconnection of the buildings. In Figure 24 options of direct or indirect cascading connection of high- and low temperature consumers are presented.

Due to investment costs, property developers in most European countries often implemented standard heating systems (in most cases radiators) in their buildings, regardless of the type and year of construction. As a consequence, the required temperature levels are often similar in different building types and ages. Therefore it is usually not possible to interconnect buildings as described in Figure 24 without further action. For existing buildings, to reduce the temperature levels, different measures like thermal retrofitting, exchange of radiators and hydraulic balancing can be implemented. By optimising/reducing the required temperatures in individual buildings through these measures, this problem could be solved and heat cascades are possible. Another option is to integrate new low-temperature consumers in areas where high-temperature customers are existing and where the above mentioned measures could not be implemented. However, a big challenge for lowering temperatures is the hygienic preparation of domestic hot water. Therefore different standard solutions can be used (e.g. fresh water modules). More advanced options can be found in (Basciotti 2014; Schmidt and Kallert 2017).

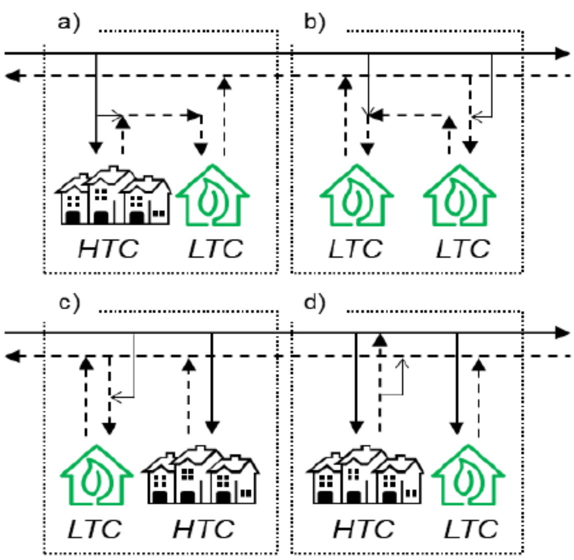


Figure 24 Option for direct or indirect cascading connection of high- and low-temperature consumers, a) direct use of HT-return, b) double cascade: indirect use of HT-consumer and direct use with an admixture, c) indirect use of HT return via the return line of the network d) indirect use via the supply line of the network, e.g. analysed in (Koefinger 2016).

For the following example, the effects of a return line connection of a new LTC in a specific section of the district heating network of Vienna are investigated based on 3 scenarios according to Figure 25.

As mentioned above the average return temperatures can be reduced in the investigated section in all scenarios 1-3 compared to the reference scenario 0. The temperatures of the return line of the network section of the different scenarios over the whole year are shown in Figure 26 (left). Especially during the heating season the possible reduction reaches the highest values due to the investigated heat cascades. The yearly average reduction of the return temperature and the maximum reduction is shown in Figure 26 (right). The results show, that scenario 2b has the highest average reduction over one year, due to the DHW preparation with fresh water modules. Scenario 3 has the highest maximum reduction. This appears in times when only the heating system of the LTC is operating and therefore is fully cascaded. The usage of the heat is realised, due to the 3-pipe-system whe-

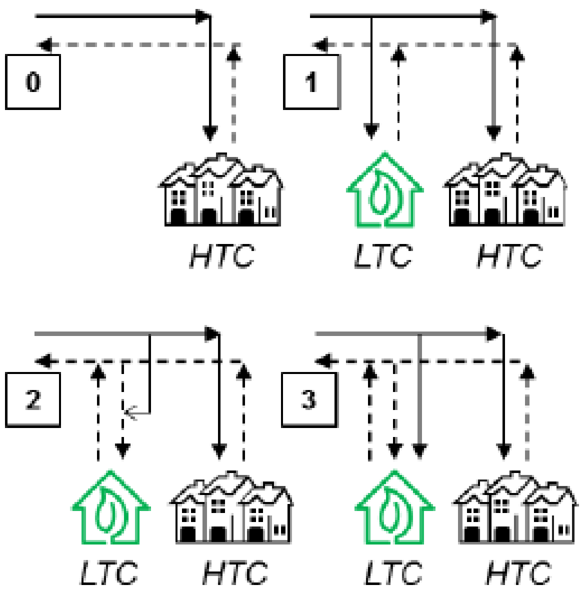
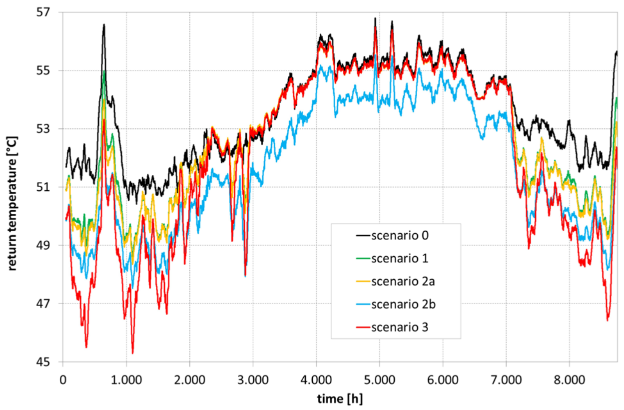


Figure 25 Connection schemes; up left: Reference scenario 0; up right: Scenario 1, Standard connection of the LT-consumer to the supply line; down left: Scenario 2, Connection of the LT-consumer to the return line; (2a: DHW preparation with standard storage system/2b: DHW preparation with decentralized fresh water module); down right: Scenario 3, Connection of the LT-consumer with a 3-pipe-system.



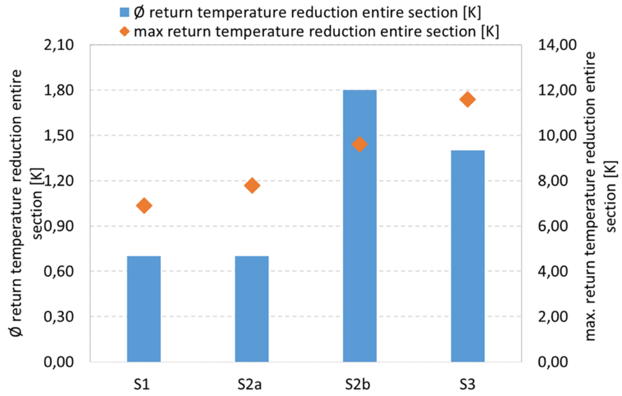


Figure 26 (left): Return temperature profiles in the investigated network section over one year (2-day average values) and (right): average and maximum return temperature reduction compared to scenario 0 (status quo).

re the space heating is supplied only via the return line of the network.

From the results, following conclusions can be drawn:

- Following technical conditions are required for realising the heat cascading: A sufficient and unidirectional mass flow, the balancing of the demand and temperature profiles between the LTC and HTC as well as measures for guaranteeing supply security such as mixing with the supply line and storages (especially for domestic hot water generation). Also measures for reducing the return temperatures such as retrofitting and hydraulic balancing of the HTC have to be considered.
- One of the main benefits of the investigated heat cascading is the possibility to connect new customers (with low supply temperature demand) to the network, that could not be connected using standard connections due to mass flow restrictions in the branch.
- In suitable network sections with high return temperature reduction potential, the local supply of low temperature sources can be very efficient. By matching the return temperature reduction potentials with potential locations for renewables and industrial waste heat, decisions for investing in local resources and return temperature reduction measures can be supported.

Significance of cascaded heat utilization in the context of a demand-adapted community supply

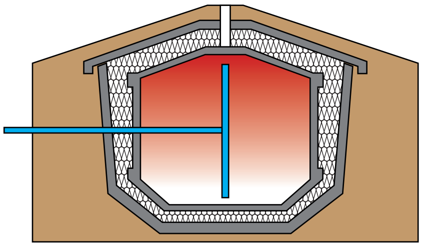
The utilization of low valued renewable energy sources (RES), such as solar thermal energy or waste heat, meets the main idea of "LowEx thinking" approach and thus helps to supply communities in an exergy efficient way. However RES supply heat with a temperature at a lower level than what is required by the majority of customers. The implementation of heat cascade connections between customers with different temperature requirements constitutes an efficient way to increase the renewables and waste heat use and to reduce the need for additional high-exergy heat supply. Thus the various possibilities of heat cascades allow improving the exergy efficiency of district heating networks.

Cascading heat utilization is not a technology, but a network connection solution to link various buildings together with high-exergy and low-exergy heat sources. In this sense cascading cannot be evaluated as such, but its impacts on the main district heating performances can be assessed, through different network indicators, among which for instance: exergy efficiency, costs, CO_2 emissions. Another possible approach is to evaluate the improvement of these indicators at the substation or (low-temperature) customer level. Indeed, the cascading connection will have more effects on the performances of the low-temperature customer, who will get low valued renewable energy sources as supply, than the standard customer, who will have minor changes in his supply mix.

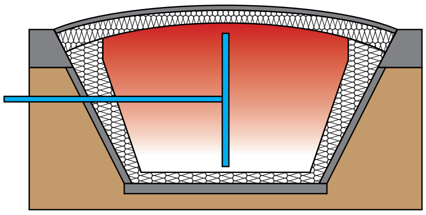
4.2.3 Thermal storages

In the context of low supply technologies short-term storage and long-term storage were discussed. Short term storage deals with time constants about a few days. This storage may concern the short term effects of the weather and the user behaviour (e.g. tapping of DHW). This storage is mainly installed at a building level (e.g. hot water tank or buffer storage for heat pumps) to have short reaction times and low distribution losses. In smaller neighbourhoods (districts) or

Tank Thermal Energy Storage (TTES)
Concrete, stainless steel or fiber reinforced polymer tanks built on or partially or totally under the ground and filled by water.
Depth: from 5 to 15 m
Suitable geological conditions: tank construction can be built in well stagnant ground, soil class II-III, as much as possible avoiding groundwater.
Usually highest specific cost compared to PTES and BTES, but lowest required volume (highest efficiency).



Pit Thermal Energy Storage (PTES)
Artificial pool closed by a lid and filled with water or gravel-water mixture.
Depth: from 5 to 15 m
Suitable geological conditions: pit construction can be built in well stagnant ground, soil class II-III, as much as possible avoiding groundwater.
Usually lower specific cost but higher required volume than TTES (lower efficiency).



Borehole Thermal Energy Storage (BTES)
Vertical boreholes in which are inserted u-pipes, also called ducts. Water runs in the u-pipes.
Depth: from 30 to 100 m
Suitable geological formations: rock or water saturated soils with no or only very low natural groundwater flow. The ground should have high thermal capacity and impermeability.
Usually lowest specific cost compared to TTES and PTES, but highest required volume (lowest efficiency).

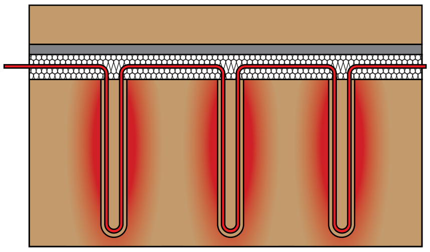


Figure 27 Different types of STES (Aguirre et al 2015)

villages short-term storages (mostly hot water tanks) are also used for several weeks to store heat generated e.g. by solar thermal energy or biomass. Long term storages are considered as monthly or seasonal storage. This seasonal thermal energy storage (STES) is large and physically more likely to apply on district scale, not attached to a building. Furthermore it can easily be used in combination with solar district heating grid (see also discussion in section 4.2.1 or 4.3.4) where solar thermal energy is gained from solar thermal collector fields or installed collectors on buildings in a district. In Figure 27 three possibilities of latent heat storage in water, soil and groundwater are shown.

The integration of STES systems in district heating grids are usually not driven by a mature technology yet. There are several pilot plants in Germany, several large plants in operation in Denmark and a few installations more all over the world, but in general the number of plants in operation is low and STES systems are a not common used technology yet (Aguirre et al. 2015).

4.3 Description of source and supply technologies

4.3.1 Gas boiler and electric heaters

Gas boilers are widely used in building heating systems and district heating systems, as main heat source as well as for peak loads. Gas boilers provide excellent energy efficiency above 80 % and are easy to use and maintain. However, their exergetic performance is very low, because the high exergy content is used to make a low exergy product instead of a high exergy product which for example electricity would be. Exergy wise worse than a gas boiler is only a direct electrical heater (Bargel 2010, Kallert 2018).

4.3.2 Combined heat and power plants (CHP)

Combined heat and power (CHP) plants produce heat and electricity at the same time. By using the heat which is produced in the process, the overall efficiency of the plant is increased. The overall efficiency is defined as the sum of the electrical and the thermal efficiency. Available CHP units include steam turbines, gas turbines, combined cycle gas/steam turbines, reciprocating internal combustion engines, Stirling engines and fuel cells (Papadopoulos and Katsigiannis 2002). Gas turbines and combustion engines are the most common types of CHP units. In both types the exhaust heat generated by the combustion of the fuel is recuperated and used to heat a hot water cycle. In case of the combustion engine, it is also possible to recuperate the lube oil heat. CHP units are available from several kW to MW which makes them suitable for individual buildings as well as district heating systems. A good overview of CHP systems is given in (Onovwiona and Ugursal 2006, Wu and Wang 2006).

Significance of CHP plants in the context of a demand-adapted community supply
Technologies and approaches that utilize the exergy available in renewable energy sources to the maximum extent possible can receive priority from an exergy thinking point of view. Whenever possible, renewable energy sources (e.g. biomass) should be utilized in a cogeneration manner rather than electricity or heat only systems. Compared to conventional heating plants, CHP units offer the possibility of coupled electricity and heat generation. If "high-valued" electricity is generated, heat is generated at the same time. The utilization of the heat increases the efficiency of the plant process. This heat can for example be fed into thermal grids to supply buildings.

A number of different methods for the assessment of the efficiency of CHP plants and the allocation of primary energy and emissions to target energies are available. In the literature a several approaches could be found (VDI 4608 2008; Hertle et al. 2014; AGFW 2014; Rosen 2008). An application example for the exergetic assessment of a cogeneration plant that supplies a small urban district using a thermal network can be found in (Kallert 2018).

4.3.3 Geothermal systems

Geothermal applications use the heat which is stored in the ground for generating thermal energy to supply buildings and districts with heat (space heating and DHW production). Geothermal heat is usually divided into deep and shallow geothermal heat (Stober und Bucher 2014). Deep geothermal heat produces heat at high temperatures which can directly be used in geothermal power plants e.g. based on an ORC (organic ranking cycle) or a Kalina processes (ITG 2018), while the shallow geothermal heat usually needs a temperature lift to higher temperatures via a heat pump. Although there is no fixed depth separation between shallow and deep geothermal heat, usually a depth of 400 m is taken as limit for shallow geothermal heat (Stober und Bucher 2014).

Amongst building heating technologies or LTDH supply the shallow geothermal heat is more common, with three different heat extraction types (see Figure 28). One is an open well system with cold water injection and hot water extraction using two separated boreholes (open loop GSHP). The second option is a geothermal collector which are horizontal closed loop pipes in a depth of a smaller than 5 m, while the third are vertical ground source heat exchangers with a closed loop pipe. Vertical ground source heat exchangers commonly use three different pipes in the building heating applications, which are U-pipes, double-U-pipes and coaxial pipes (Stober and Bucher 2014). Geothermal heat is used to heat individual buildings as well as district heating systems. A good overview of geothermal systems is given e.g. in (DGGV 2016, Manzella 2018).

Significance of geothermal systems in the context of a demand-adapted community supply
The use of geothermal sources meets the fundamental idea of "demand adapted supply" respectively "exergy thinking" and thus helps to supply communities in an exergy efficient way. In particular in the case of shallow geothermal heat the heat gained from the ground matches the energy demand of the building without high destruction of exergy.

The use of geothermal heat has, in particular, a strong influence on the performance of a geothermal or ground sources heat pump (GSHP) (see also discussion in section 4.3.7). When using geothermal sources the Coefficient of Performance (COP) of a GSHP increases with increasing temperature of the geothermal source since the demand of "high-valued" electricity for driving the compressor of the heat pump decreases significantly. In the case of using swallow geothermal heat a COP of a GSHP of approximately 4-6 can be achieved (Kallert 2018). In the case of deep geothermal heat a COP of about 8-10 can be achieved (Sanchez 2014). If geothermal energy is used in power plants (e.g. are based on ORC process), the effects are similar to those of CHP plants (see discussion in section 4.3.2). The utilization of "low-valued" "waste heat" (as a by-product) increases the efficiency of the generation of "high-valued" electricity (ITG 2018).

An exergy assessment approach for the evaluation of swallow geothermal energy used by GSHP can be found in (Kallert 2018). An evaluation approach for deep geothermal heat used by HP can e.g. be found in (Sanchez 2014).

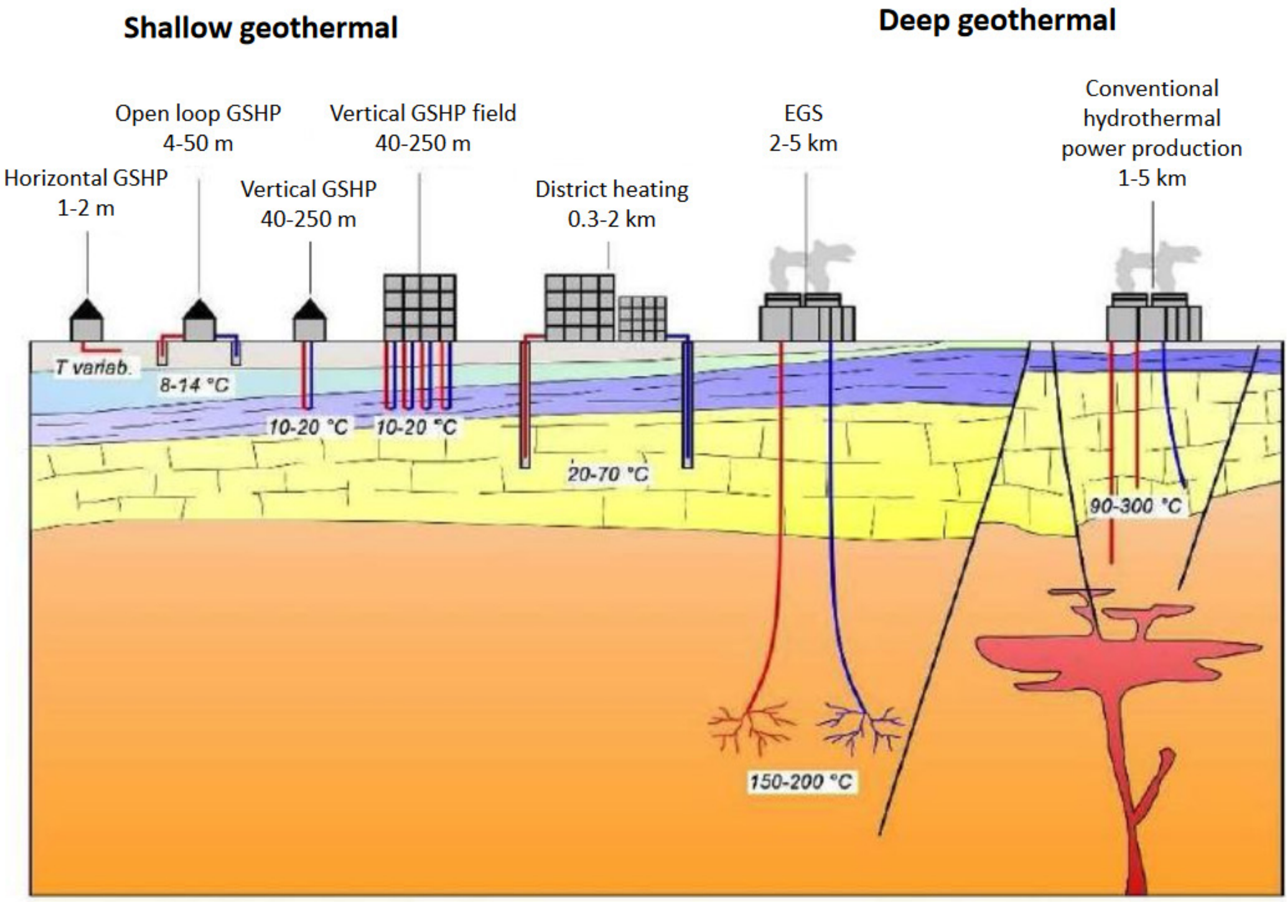


Figure 28 Examples for shallow and deep geothermal heat (Manzella 2018)

4.3.4 Solar Thermal Systems

Solar thermal systems usually consist of a solar collector to heat the heat transfer medium and a thermal energy storage (TES) to separate the heat generation from the demand. The incoming solar radiation heats up the heat transfer medium which is led out of the collector to the TES, while at the same time cool heat transfer medium is directed into the collector.

There are many different types of solar thermal collectors such as flat-plate, compound parabolic, evacuated tube and parabolic trough collectors. A good overview about the characteristics of collector types can be found in (Kalogirou 2004). Taking into account the application purpose of the collector (e.g. individual building or community heat supply) different types of storage facilities (e.g. buffer or seasonal storage) can be used. Different types of storage systems are discussed in section 4.2.3.

In individual buildings, solar thermal collectors are often used for DHW production and rarely for proving space heating. However, large collector fields combined with seasonal storage systems can also supply cities and communities using solar district heating systems (SHD) (see also section 4.2.3) (Schmidt et al. 2004). Basically there are different ways of feeding heat into the SHD grid: Figure 29 shows a centralised solar field, which is connected either to a large combined heat and power plant (district heating) or a heat-only boiler station (block heating). Figure 29 (right) shows a distributed solar field connected to a subsection of the heating network (Epp 2015).

Significance of solar thermal collectors in the context of a demand-adapted community supply

The use of solar thermal collectors for the use of the heated collector fluid for heating purposes, meets the fundamental idea of "demand adapted supply" respectively the "lowex thinking" approach and thus helps to supply communities in an exergy efficient way. The heat gained from the solar thermal collectors matches the energy demand of the building without great destruction of exergy. Another very important advantage of this approach is that direct use of solar radiation instead of degrading other high quality energy resources found in nature is advantageous (Torio and Schmidt 2011).

For the evaluation of solar thermal collectors often the methodology described by (Torio and Schmidt 2011) (see also Torío et al. 2009; Torío 2012;Jentsch 2010; Kallert 2018) is applied, where the temperature of the fluid circulation in the solar thermal

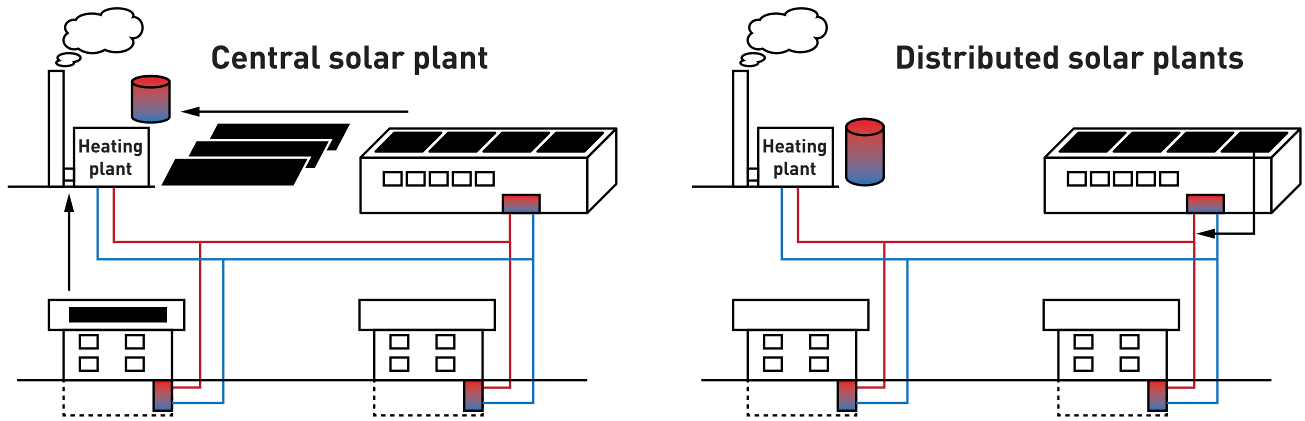


Figure 29 Different ways to feed solar heat into a district heating grid: (left) in individual buildings and (right): distributed solar field (Dalenbäck 2015).

collectors is used for evaluation. It should be noted that there are different approaches for this, and when optimizing the use of solar radiation, broader system boundaries are more suitable (Jansen and Meggers, 2016, Kallert 2018).

Approaches for exergetic evaluation of SDH are e.g. found in (Schmidt and Kallert 2017, Kallert et al. 2017, Rezaie et al. 2018). As part of this work the potential benefits to improve performance of solar feed low-temperature district heating networks when using an exergy approach is demonstrated.

4.3.5 Solar photovoltaic thermal

Photovoltaic (PV) panels transform incoming solar radiation into electricity using the photoelectric effect of semiconducting materials in solar cells. While PV panels generate electricity, however, more than 50 % of the incoming solar radiation is transformed into heat (Chow 2010). The PV panel's efficiency decreases with its temperature. Therefore, cooling the panel by a thermal collector not only maintains the design efficiency of PV cells but also generates hot water so that the overall component efficiency can be increased. This concept that integrates photovoltaic and solar thermal components is called a photovoltaic thermal (PVT) collector. The temperature issue in PV panels can thereby be addressed by various cooling technologies, including a PVT collector cooled by forced water circulation (Siecker et al., 2017). The PVT collector generates electricity while the coolant ensures good working conditions for the solar cells and at the same time, makes the generated heat available for useful applications. Overview of PV technologies and PVT collectors are e.g. given in (Parida et al. 2011, Chow 2010). The performance improvements and benefits of integrating PV and thermal systems in a single unit to produce both electricity and low grade (low exergy) heat is also reviewed in (Sathe and Dhoble, 2017).

Significance of photovoltaic thermal collectors (PVT) in the context of a demand-adapted community supply

Technologies and approaches that utilize the exergy available in renewable energy sources to the maximum extent possible can receive priority from an exergy thinking point of view. Whenever possible, renewable energy sources, including solar energy, should be utilized in a cogeneration or polygeneration manner rather than electricity or heat only systems. PVT technologies are considered as one option for such an approach given that the incoming solar energy is used to produce not only electricity but also thermal energy from the residual heat (Kilkis and Kilkis 2016). In Copenhagen, for example, building integrated PVT collectors are being tested to maximize the contribution of renewable energy sources in the local energy mix (Perers et al., 2014). PVT systems are especially useful for LowEx buildings while they may satisfy both their low exergy thermal and low power loads more easily and efficiently. PVT collectors can further be integrated in support of a low temperature (low exergy) district heating scheme in a fourth generation district heating concept at the community level.

Based on the Rational Exergy Management Model, PVT collectors are evaluated based on the level of match between the supply and demand sides (Kilkis 2011). While the exergy of the incoming solar energy for a particular location is the same for photovoltaic panels and PVT collectors, PVT collectors can satisfy an extra exergy demand based on the provision of thermal energy for local use. Given such utilization, the rational exergy management efficiency is higher for PVT collectors than for photovoltaic panels that produce only electricity. This is also true when PVT systems are compared with solar thermal collectors. A proposal to implement PVT panels to improve the circular economy of a dairy farm based on an approach for exergy matching in addition to other options, including combined heat and power using bioenergy, was put forth in (Kilkis and Kilkis 2017). The results proved to have both primary energy and primary exergy savings. According to the approach, the exergy of all available energy resources should be utilized to the greatest extent that is possible, including the recycling of residual heat to become inputs for other processes. A thin film thermoelectric generator was further integrated into the PVT array to minimize the temperature gaps that were previously left unutilized, i.e. the points of exergy destruction (Kilkis and Kilkis 2017). Other studies in the literature include exergy analyses at the component level for PVT systems (Sobhnamayan et al. 2014) as well as the optimization of design parameters of a single channel hybrid PVT system based on a genetic algorithm (Singh et al.2015). The energy and exergy efficiency of a flat plate air based PVT system was also compared (Srimanickam et al. 2015) while a photovoltaic thermal compound parabolic concentrator (PVT-CPC) was analyzed (Atheaya et al. 2016). In such cases, the exergy benefits of PVT systems are clearly underlined.

4.3.6 Waste heat

Often industrial waste heat is at temperatures below 200 °C which makes the utilization for another industrial process difficult, technically or economically (Fang et al. 2013). Using waste heat from industrial processes can be a good alternative to traditional heat sources in district heating systems, wherever it is available. With the use of low temperature district heating, this type of heat sources becomes more available, as most of the low exergy industrial waste heat ranges mostly between 30 °C and 100 °C (Fang et al. 2013). Other sources of waste heat are data centres, as for example the 2 MW data centres in Helsinki (Ebrahimi et al. 2014). Low temperature waste heat could also be used as heat source for heat pumps to produce heat at a higher temperature for example waste heat from sewage drains.

A good overview of industrial waste heat utilization is given in (Fang et al. 2013) and of data centre waste heat utilization in (Ebrahimi et al. 2014).

Significance of waste heat in the context of a demand-adapted community supply

The utilization of low valued waste heat (low exergy industrial waste heat) meets the fundamental idea of the "lowex thinking" approach and thus helps to supply communities in an exergy efficient way, since "waste heat" can be used by heat pumps or in a cogeneration process and in so-called energy cascades.

The use of waste heat has in particular a strong influence on the performance of a heat pump (HP). By increasing the source temperature, and consequently the COP, the demand of electricity decreases significantly (see also discussion in section 4.3.3). If waste heat is used in power plants (e.g. based on ORC process), the effects are similar to those of CHP plants (see discussion in section 4.3.2) and the usage of geothermal energy (see section 4.3.3).

Approaches for exergetic evaluation of waste heat usage in district heating systems could be found in (Torio and Schmidt 2010).

4.3.7 Heat Pump

A compression heat pump uses mechanical energy to bring heat at a low temperature to a higher temperature using a thermodynamic process. Usual heat sources for space heating (incl. DHW preparation) applications are surrounding air or geothermal heat. Another option is the implementation of a solar thermal collector to set up a solar assisted heat pump system in which the evaporator takes the heat from the solar collector. Heat pumps are widely used in individual buildings and in combination with geothermal heated district heating systems. To assess heat pumps the COP is used which is defined as the ratio of the useful heat Q provided to required work W. A good overview of different heat pump applications is given in (Hepbasli and Kalinci 2009).

Heat pumps are used to utilize the heat stored in low temperature sources. Usually, heat from the environment (soil, water, air), industrial processes, wastewater, or other low-temperature sources is used and raised to a level required for heating purposes by electrical energy (Biermayr 2012).

If the source is natural, as external heat sources such as waters (sea, ground or river water) or soil (deep boreholes, geothermal), these must be examined for the possible amount of heat extraction and the possible temperature. It is also important to pay attention to seasonal fluctuations. If non-natural external sources, e.g. if waste heat from industrial processes or wastewater heat is used the respective temperature level and the possible extraction power must be clarified and the system (for example heat exchangers, pumps, pipelines) dimensioned accordingly.

The design of heat pump systems for thermal networks (on a commuinity level) is mainly dependent on the heat source. Depending on the possible extraction capacity, the heat pump can be dimensioned. The heat exchangers and the unit itself are designed for the respective frame conditions. Other decisive parameters are site-specific restrictions and legal issues. Furthermore, the heat dissipation system (here the thermal network) must be suitable (e.g. low supply temperature levels) for the operation of the heat pump. Since heat pumps for district heating applications are in most cases not standard or series products, the devices are designed by the respective manufacturer in cooperation with the network operator for the specific application.

As a basic rule for the design of heat pumps in thermal networks, it can be assumed that the basic load should be covered by heat pumps. This ensures that the heat pumps have a high number of full load hours. In addition, the required installed capacity can be kept small (including lower investment costs) and still cover a significant part of the heat load.

Depending on the connection variant, heat pumps can also be integrated into the return line in order to ensure high efficiency at lower temperatures (Schmidt and Kallert 2017). The maximum flow temperature required for some district heating networks can be reached by post-heating with e.g. combustion processes or e-boilers. Otherwise, the design of heat pumps may be similar to that of other producers of district heating networks, taking into account such parameters as heat load, simultaneity factor, etc.

When designing heat pump systems in the small power range or for individual buildings, the main focus is on adapting the heat pumps to the required heating load of the building, including the provision of domestic hot water. In heat pumps in thermal networks, these are in most cases operated in combination with additional (peak load) producers. For this reason, the possible extraction power of the heat source is considered here in the dimensioning or a cost optimum between investment costs and possible operating costs is sought in order to achieve the amortization in a few years. Nevertheless, of course, in thermal networks, the heat pump performance must be adapted to the temperature decrease in the network. The heat sink is in this case the district heating system or the customers connected to it. The design of the network must therefore be the same as for conventional heat generators. In order to create suitable conditions for heat pumps, the temperature level of the network (and therefore also the customer) should be as low as possible. As a result, the heat pump can be operated particularly efficiently and cost-effectively. The heating systems of the customers must therefore also correspond to the low temperatures. Low temperature heating systems should therefore be present or installed in the buildings. The distribution of heat in networks with low temperatures, due to the smaller possible spread between flow and return, usually higher volume flows and thus sometimes larger pipe diameter, must be able to transport the corresponding heat. For new networks, this fact can already be taken into account during planning. In the case of existing networks, this is usually not possible, which requires an early clarification as to whether the low temperatures are possible or whether additional after-heating elements (for example, boilers, electric heaters, etc.) may be necessary. Furthermore, the integration of thermal storage or the storage capacity of the network must also be taken into account. Any peak loads that require higher powers and / or temperatures can be damped thereby.

Significance of heat pumps in the context of a demand-adapted community supply
The utilization of heat pumps can help to supply communities in an exergy efficient way. The efficiency of the heat pump is usually dependent on the temperature level of the source used (see also discussion in chapters 4.3.3 and 4.3.6) The higher the source temperature the lower the use of "high quality" electricity for the compressor for a given supply temperature range.

However, in the context of the community energy supply the heat pump plays a key role in the coupling of the sectors "electricity" and "heat". Particularly in times when a lot of PV or wind power is generated, the produced electricity cannot be consumed at that time and the transportation capacities are too limited to transport the electricity to other users. To overcome this challenge of temporary "surplus energy", the coupling of the electricity and heat sectors by using a heat pump are one feasible option (Schmidt et al. 2015; Yu 2013; Kallert 2018). This strategy is also known as "power-to-heat" (P2H).

At a first glance, P2H is not a good solution from an exergetic point of view, since the overall working potential of the energy flow cannot be used. However, in the case of the application of P2H technologies, it must be taken into account that the central objective of the energy transition is the decarbonisation of the total energy systems by using electricity from 100 % RES (Gerhardt et al. 2015). In turn it is not aimed to increase the share of the renewables due to the flexibilization by producing excess electricity. From an exergetic point of view, the grid extension is the more favourable solution compared to P2H. This is not in all cases possible. As a result, electricity from renewables is only used for heating purposes if the surplus electricity would otherwise have to be curtailed. The main task of the exergy assessment of P2H is to support the "supply-adapted demand", in case if electricity is used for heating purposes. Furthermore in many cases, conventional fuels (coal, gas, oil, etc.) are saved. The basic idea of the exergetic evaluation thus corresponds to the basic idea of the P2H to use energy resources carefully and economically (Kallert 2018).

Approaches for exergetic evaluation of heat pumps could be found in (Kallert 2018, Toniolo 2018).

4.4 Conclusion

In the course of this chapter technologies allowing a flexible supply of different demands with maximal share of low-valued local and renewable energy sources are identified and described.

The technological considerations include both demand- and supply-side aspects. Hence, the requirements for efficient buildings and user behaviour are discussed. Furthermore decentralized supply solutions and storage technologies, which serve as interfaces for community energy systems, are compared. Subsequently different supply technologies (e.g. heat pumps or solar thermal collectors) are described.

As part of the supply solutions the significance of the energy supply units regarded in the context of a demand-adapted community supply was discussed. Furthermore, approaches for the exergetic assessment of the respective system component were elaborated.

5 Case Studies across scales

5.1 Introduction

This chapter gathers many different case studies, from different scales (building, district and city) and different countries, where the exergy thinking was used through various methods and tools in order to answer specific questions such as:

- How to improve the control of the system considered?
- How to increase the use of low-temperature sources?
- How to implement cascading solutions into district heating networks?
- How to make the best usage of surplus energy and electricity?
- How to integrate more renewables in the energy mix?
- How to reduce the heat losses in the network, e.g. in order to reduce the primary energy consumption and CO_2 emissions of the system considered?

For each case study key information are given:

- Development and/or improvement of the control strategy of the system considered: How to apply the exergy analysis in order to control building energy systems and reduce their energy consumption?
- Increase of the use of renewables and alternative energies: Under which conditions is the decrease of the exergy use related to an increase of the use of renewable and alternative energies? How can the low-exergy approach help towards the development of more sustainable heating systems?
- Improvement of the system performances: How can the exergy analysis and LowEx system components contribute to improve the energy performances (reduction of operating temperature, CO_2 emissions, primary energy consumption, distribution heat losses, etc.)?

Figure 30 gives an overview of all the case studies reported in this Guidebook. They are classified by scales (buildings, district and city) and challenges. Although

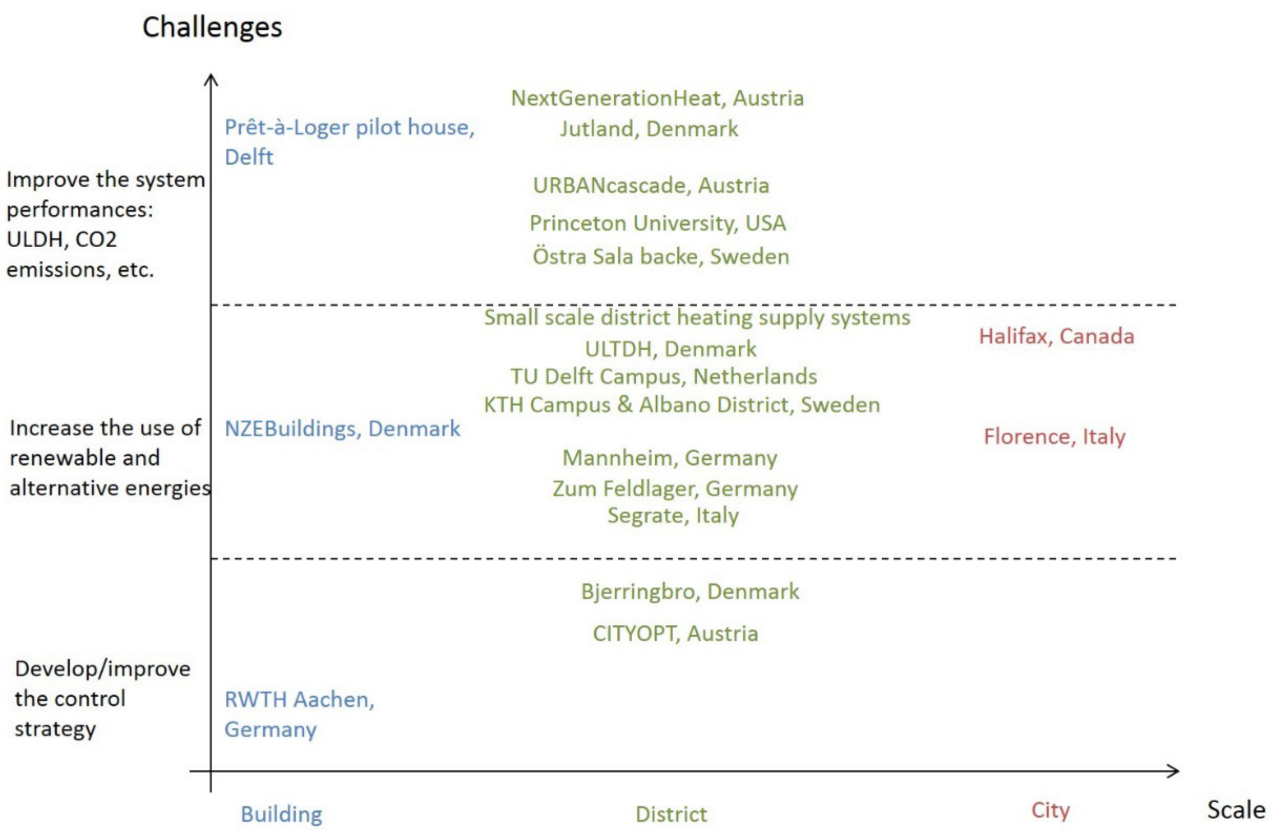


Figure 30 Overview of all reported case studies. For each case study, detailed descriptions can be found on the Annex 64 website (Annex64 2018) and in the detailed case study report (Maguerite and Schmidt 2018).

some cases could be related to several issues, three main challenges were identified:

5.2 Building scale

5.2.1 House as a power plant, exergetic improvement of Prêt-à-Loger pilot house

Prêt-à-Loger is an energy neutral refurbishment concept for Dutch terraced houses developed by the Faculty of Architecture of the TU Delft, The Netherlands. This research investigates the possible improvement of the energy performance of a single house, and the potential improvements when up-scaling to district level (1000 dwellings), by using exergy analysis of the system performance for the Prêt-à-Loger house (energy neutral renovation pilot) built in the TU Delft campus. The study starts from the optimization of the Prêt-à-Loger energy neutral house improved design (resulting in a 140 % energy positive design). The study then shows the up-scaling of the single house design to the district level, where 1000 dwellings are considered.

This research aims to highlight the possibilities provided by exergy analysis in energy neutral renovation design, for single house and up-scaled energy optimization. To achieve these targets the improvement potential of the Prêt-à-Loger system performances by using exergy analysis and LowEx system components are investigated. Furthermore, the exergy efficiency changes and added value in the design of LowEx single building renovation as well as an up-scaled (1000 houses) district solution are analysed.

Exergy analysis provided crucial insights for system optimization-improvement of both the single house and the up-scaled 1000 houses system. An exergy based simulation model was made in TRNSYS (TRNSYS 2014) using the detailed building simulation component (TRNbuild) (TRNSYS 2005). Exergy analysis showed a crucial role in the analysis and design for all the steps presented: optimized-improved design and up-scale solution (DeLeo 2016).

5.2.2 Exergy-based control strategy for HVAC systems

The enhancement of building automation systems offers the opportunity for a large reduction in the final energy demand of buildings. In this research project, ways to apply the thermodynamic method of exergy analysis on the control of complex building energy systems are analysed. The focus is on the improvement of energy efficiency while ensuring indoor air quality and thermal comfort. Hence the main objective is to develop an exergy-based control strategy for building energy systems. As part of this, exergy analysis is applied to control building energy systems and reduce their energy consumption.

Figure 31 Prêt-à-Loger pilot house at Solar Decathlon 2014, France (Pretaloger 2017)

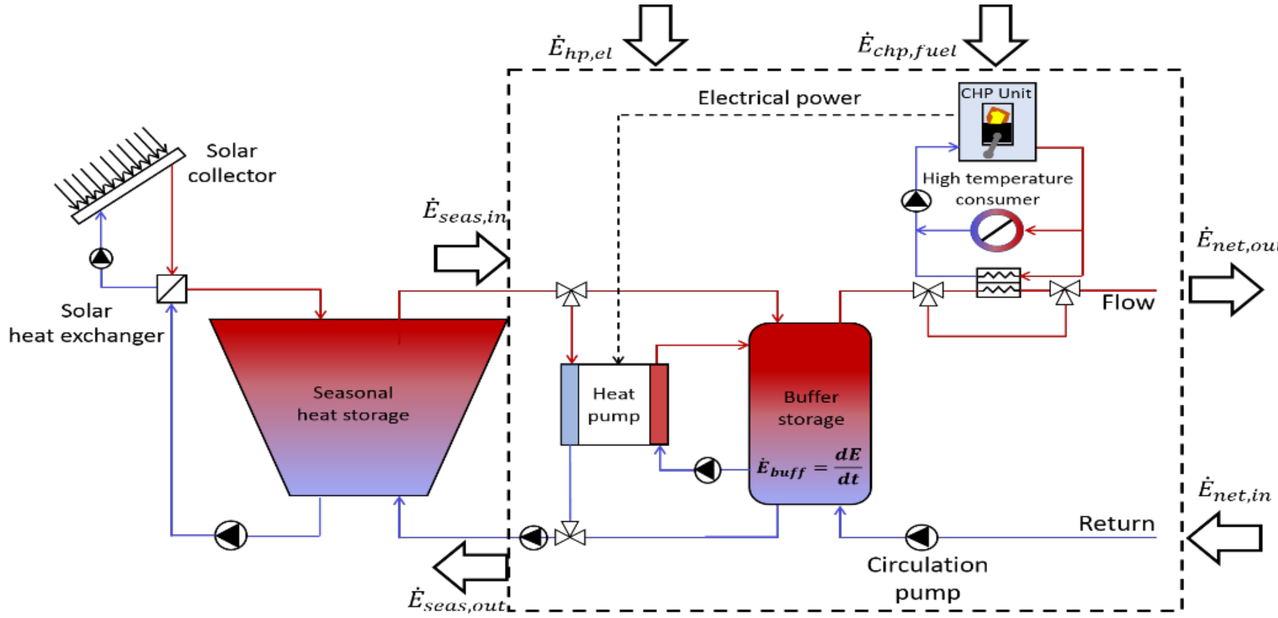


Figure 32 Exergy balance in the generator subsystem considered in the simulation case study

The project showed that exergy-based control is suitable to achieve efficient building operation. Using dynamic simulation models, the exergy analysis can be fully automatized and used for model-based control. The approach was demonstrated in simulation and real-life demonstration (Baranski et al. 2017).

5.3 District Scale

5.3.1 Geo-solar low-temperature district heating for the new housing development "Zum Feldlager"

The planned new housing development "Zum Feldlager" (Kassel, Germany) comprises of 131 residential buildings with a high energy standard. The heat supply concept is based on an ultra-low-temperature district heating (U-LTDH) network with a design supply temperature of 40 °C. Thus, the DH supply temperature level is adapted to the temperature requirements of modern floor heating systems. The network is fed by a ground source heat pump (GSHP) supplemented by a buffer storage and an electric peak load heater. Depending on the supply variant, a Borehole Thermal Energy Storage (BTES) acts as source within the space heating period (winter) or as thermal storage outside the space heating period (summer). Uncovered solar collectors are intended charging the BTES with low-temperature heat. Outside the space heating period, individual solar thermal systems are used for domestic hot water preparation.

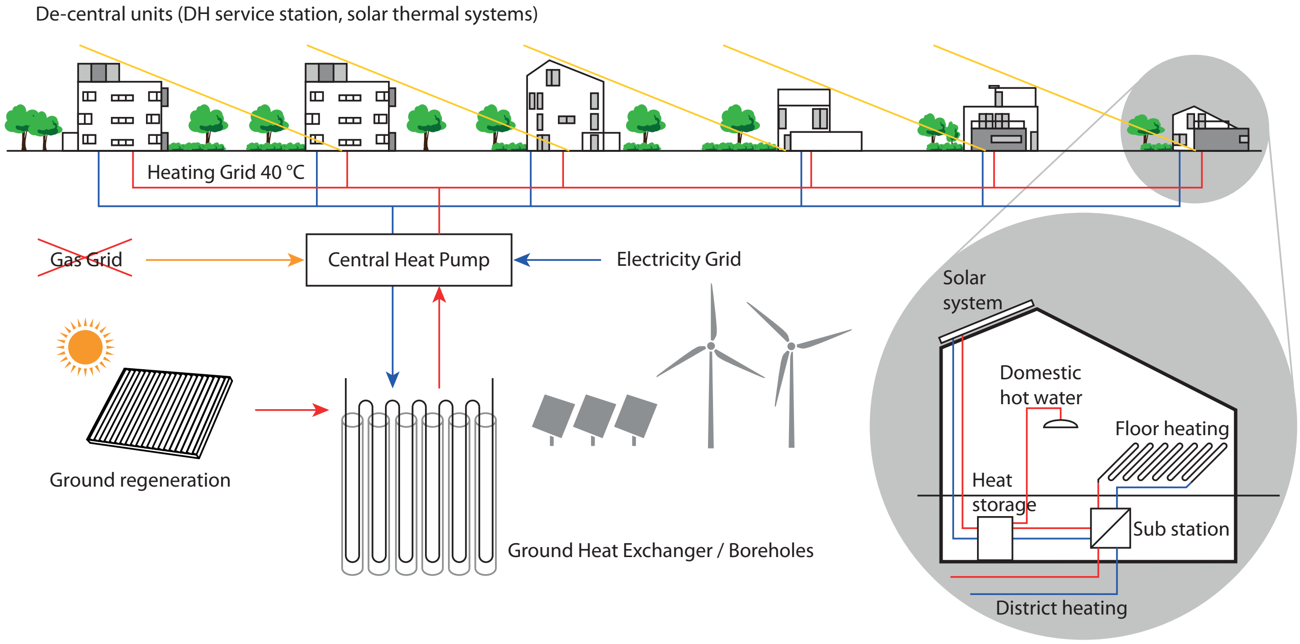


Figure 33 Supply scheme of the planned new housing development (Schmidt and Kallert 2017).

As part of the project, a thermal simulation model was developed. Applying a seasonal operation, which implies a switch-off of the DH network outside the space heating period, avoids heat distribution losses. Within the space heating period the DH network can be used to preheat the cold water for DHW preparation. The optimisation of DHW preparation results in a low electricity need of around 10 % for DHW boost (single family houses) and high solar fraction of 60 %. The simulation results show that the overall system achieves 80 % share of renewable heat using low-value heat from distributed solar thermal systems for DHW preparation and a GSHP for space heating. Following the low-exergy principles, low-value heat sources like solar and geothermal are used to supply heat at a low temperature level meeting the temperature need of floor heating systems perfectly (Schmidt et al. 2017).

5.3.2 Princeton operating case compare/contrast

This case study consists of the Princeton University campus (New Jersey, USA) heating system with 160 buildings and a heat demand of 132 GWh during the heating period (year 2013/2014). The demand data of the Princeton University campus heating system was kindly provided by Princeton University, USA. The main objective of this case study is the evaluation of alternatives to the current Princeton University heating system in order to make the heating system more sustainable. Exergy analysis is used in order to find a system with reduced exergy destruction and exergy use.

As part of the study three different heat supply scenarios with a supply temperature of 50 °C are investigated:

1. CHP: CHP plant with a buffer TES and a gas boiler for peak loads.
2. Geo: Heat pump with a geothermal borehole field and a buffer TES.
3. CHP + Geo: CHP plant coupled with a heat pump and a geothermal borehole field and a buffer TES.

The evaluation of the results show that with increasing share of geothermal energy, the fossil energy input decreases, while at the same time the input of renewable energies increases. Although fossil energy sources are conserved, the CO_2 emissions stay rather constant with increasing share of geothermal energy due to the energy mix in the electricity grid. With more renewable energies in the electricity grid, an increasing share of geothermal energies would be beneficial in terms of saving fossil energy, having a lower overall exergy input and also reduced CO_2 emissions (Falk et al. 2016).

5.3.3 Evaluation of community heating systems based on exergy analysis. 11 buildings in Mannheim, Germany

This case study consists of a building group of 11 buildings connected via a small district heating system. The total heat demand in 2013 is 263 MWh and the electricity demand is 59.4 MWh. The heat demand data of the buildings was kindly provided by the local utility company MVV Energie AG Mannheim, Germany. Main objective was to increase the use of renewable and alternative energies and to decrease the exergy use for the same energy demand.

Five different heat supply scenarios with a supply temperature of 50 °C are studied:

1. CHP: CHP plant with a buffer thermal energy storage (TES) and a gas boiler for peak loads.
2. Gas: Gas boiler as only heat source.
3. CHP + Geo: CHP plant coupled with a heat pump and a geothermal borehole field and a buffer TES. The nominal power of the heat pump is 68 % of the combined nominal power of heat pump and CHP plant.
4. Geo: Heat pump with a geothermal borehole field and a buffer TES.
5. Solar: Solar thermal system with a seasonal TES and a gas boiler as backup.

Exergy analysis is used to find a system with reduced exergy destruction and exergy use. The evaluation of the results show that the CHP scenario has good results regarding energy input, energy efficiency and GWP. The Geo scenario has good results regarding the exergy input and the exergy efficiency, it has the lowest fossil energy input and the lowest GWP. The Geo scenario performance would strongly increase with an increase of renewable energies in the electricity grid. The CHP + Geo scenario offers a compromise of the CHP and the Geo scenario, with its results ranging between the CHP and the Geo scenario (Falk 2018; Falk et al. 2017).

5.3.4 Exergy-based analysis of renewable multi-generation units for small scale low-temperature district heating supply

The target of the generic case study is to demonstrate the advantages of exergy-based assessment of low temperature district heating supply. To achieve this target a model of a building group is developed and different technology scenarios are simulated. The simulation studies comprise different supply scenarios, based on fossil and renewable energy sources. The different renewable energy supply units are regarded individually or in two- or three-way combinations. Renewable and fossil-based supply are compared and the benefits of merging several renewable energy suppliers for a small building group with a high energy standard are identified. For evaluation and identification of the best supply solution, the exergy-based assessment method is applied. Additionally other assessment parameters such as estimation of CO_2 emissions and full-costs analysis are added to exergy assessment in order to compare the different supply solutions.

The evaluation of the scenarios shows that the combination of innovative supply strategies and exergetic assessment leads to a "holistic understanding" of the energy conversion chain. Furthermore, exergetic analysis shows optimization potential, beyond energy analysis and offers prospects for an optimized community supply. But the exergetic analysis is limited regarding sustainability (implementation of RES) since only statements regarding temperature levels are made. In order to increase the comparability of exergy assessment and to involve other important factors, which play an important role on communal level, economic considerations and analysis of emissions should also be included in the evaluation (Kallert et al. 2017).

5.3.5 Politecnico di Milano-ABC dept. – new district energy concept in Segrate

This case study regards the design phase of a new development district in northern Italy. The district includes mostly residential buildings and a small share of commercial ones. The energy scenario comprises a biomass cogeneration, PV systems and heat pumps. A low-exergy district network supply space heating and cooling and DHW. The objective is to define an energy supply scenario for that new development district in Italy, by considering renewable energy sources (RES) integration and low-exergy solutions.

The system includes definition of nZEBs (compare also 4.1.1) low exergy district systems and RES. The GICOP-DHS (Geographic Information-based Cost Optimal Planning of District Heating System) tool (see also section 6.1.3) was used to generate the district heating network. A component based input-output analysis was applied for the exergy analysis. The energy scenario for the new settlement reveals an estimated low energy demand, thanks to high buildings standard and low thermal losses among the network, wide energy share produced from renewables and good exergy efficiency, compared to traditional thermal systems.

The presented case study refers to the energy scenario developed within a larger project of a new smart settlement in Northern Italy, "Milano4You", based on a private commitment (Milano4You 2017; Aste et al. 2017).

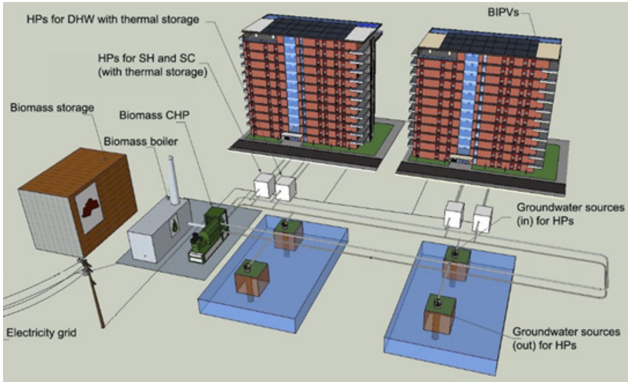


Figure 34 General schema of the selected energy scenario.

5.3.6 The application of BEX to a portion of urban system in the city of Florence

The model developed in a PhD thesis (Baldi 2015) integrates several requirements, and both the First and Second Law of Thermodynamics analysis (Moran and Shapiro 2004). Modelling a black box approach, it uses with flexibility the available data of energy and material utilization in an urban space, and immediately and comprehensively defines the environmental impact of energy use. The model is applied to a portion of the real urban system of Florence, in Italy, using the existing data. The database, developed for the Piano Energetico Ambientale Comunale (PEAC) of 2006, is used. The geo-referencing energy use maps and a hybrid statistical model to evaluate the urban energy needs of the buildings population was elaborated by the Department of Energy Engineering of the University of Florence. Main target of the research was to analyse the exergy balance of a geo-referenced urban district. The objective of this case study is the application of the model BEX to the available data for the city of Florence (Baldi 2015).

5.3.7 Heating buildings with direct electrical heating by storing heat in the thermal mass during off-peak hours using predictive control

For this case study the space heating demand is predicted for the upcoming day based on weather forecasts (solar radiation and outdoor temperature) at midnight. Based on the predicted heat demand, an electrical floor heating system during off-peak hours is operated to store the heat in the building construction and release the heat during the next day. The aim is to use surplus renewable electricity during night time instead of electricity during daytime. A nZEBuilding (compare also 4.1.1) has been used as case and measurements have been executed during February 2016. Furthermore, a solution for heating nZEBuildings in areas outside district heating with surplus off-peak electricity will be demonstrated.

A nZEBuilding could be heated with surplus (renewable) electricity during off-peak-hours (00:00-06:00) by storing electricity as heat in the concrete floor construction. The heat will be released during the next day, providing sufficient space heating without causing thermal discomfort for most of the time, except for an extremely cold night (-12 °C). The potential low electricity price during the night period also helps to reduce the cost by electrical heating (Harrestrup et al. 2016).

5.3.8 New concept of electric supplementary heating based on micro tank for domestic hot water preparation with ultra-low-temperature district heating supply

Five detached houses built in 1997-99 located in Jutland, Denmark were selected to have electric booster installed in their substations. The main district heating (DH) network was retained, but a mixing shunt was added at the upstream point to those five houses. The shunt decreases the DH supply temperature from 70 °C to 40 °C as analogue to ultra-low temperature district heating (ULTDH) supply temperature. The main objective of the project is to develop a prototype of a new DH unit suitable for ultra-low temperature district heating supply (40 °C) with an electric booster for the domestic hot water and demonstrate the technical and economic feasibility.

As part of the results it was shown that 40 °C DH supply temperature assisted with local electric booster maintains the thermal comfort of DHW for the consumers. Electricity consumption for electrical booster accounted roughly 3 % of the total heat demand (space heating and DHW). The DH heat loss can be reduced by 50 % compared to scenarios with temperatures 80 °C / 40 °C / 8 °C. The exergy analyses based on an annual measurement show that the ULTDH system with local electric booster has higher exergy efficiency compared to the existing DH system (Brand and Gudmundsson 2016).

5.3.9 Ultra-low temperature district heating (ULTDH) in Bjerringbro city for heating and cooling

The case study located in Bjerringbro, Denmark consists of 21 single family houses supplied with ultra-low temperature district heating (ULTDH) at 46 °C with local supplementary heating devices. The system is a cascaded energy system. During the winter a ground source heat pump (GSHP) unit is used for heat production. The ground water is used to cover the cooling demand of a pump factory nearby during the summer. A cogeneration plant (CHP) and a heat plant are supplemented for the peak load covering. The main objective of the case study is to increase the use of renewable energy as heat sources for district heating and to improve the efficiency of ultra-low temperature district heating.

As part of the project, analyses of energy, exergy, and economy are carried out together to characterise the real performance of case system. The evaluation of the results shows that case system (ULTDH supplied by GSHP) has higher exergy utilization efficiency than ULTDH supplied by CHP/heat plant as well as the normal DH (70/40 °C). By implementing ULTDH, distribution heat loss can be saved substantially.

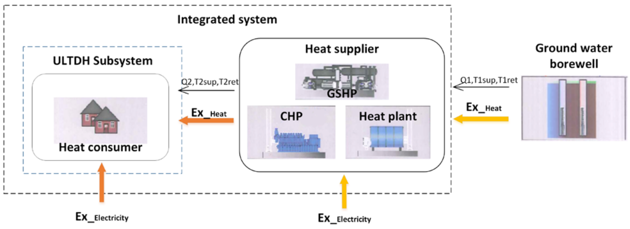


Figure 35 Schematic of the ultra-low temperature district heating system utilizing ground source central heat pump

5.3.10 Cascading solutions between different building types

The aim of the project “URBANcascade“ is to increase the potential of waste heat and renewable energy sources and the efficiency of urban district heating and cooling systems (measured by the reduction of primary energy consumption and CO_2 emissions) by the integration of concepts for the cascade utilisation of thermal energy. The adjustment of the temperature levels of waste heat, renewable energy carriers and the network itself plays a pivotal role.

In order to reach these objectives, the optimisation potentials within different characteristic building types were identified, synergies within building clusters were considered and the effect of these measures on the temperature levels in the urban district heating system were evaluated in different scenarios. Cascading in the DH networks optimizes the exergetic performance, since it lowers the system temperatures and in turn allows heat pumps to supply to the DH network. Integration of heat pumps at all levels is one of the main focuses of this project.

Within the project a Modelica/Dymola tool (DYMOLA 2018) was used to simulate the different scenarios and the exergy calculations were based on exergy balance equations and exergy flow equations. The results show that low supply temperatures can decrease thermal exergy supply for the low temperature customer about 28 % depending on the configuration considered. Heat cascades are possible if there are: a sufficient and unidirectional mass flow, the balancing of the demand and temperature profiles between the low temperature customer and high temperature customer as well as measures for guaranteeing supply security (Köfinger 2016).

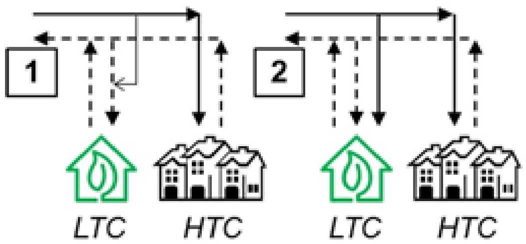


Figure 36 Connection scheme in two scenarios.

5.3.11 Economical and environmental optimal design of SH and DHW for 4 DH schemes in Austria

In this project, a static assessment tool and dynamic network simulation will be applied to develop, evaluate and test concepts for the economically and ecologically optimized supply of space heating and warm water, by means of district heating, to passive and low energy buildings at the example of four case studies. These concepts are based on low supply temperatures thus allowing to exploit currently unused (renewable) energy sources and to reduce heat losses and investment costs. The aim is to develop and evaluate economically and ecologically optimized concepts for low temperature district heating networks tailored to different regions in Austria using 4 case studies (only 2 cases are presented here). Furthermore, optimized solutions to the problem of hygienic warm water generation are worked out, taking into account heat pumps and other external energy sources.

In this example, low-temperature district heating (LTDH) with supply temperature between 35 °C and 65 °C is compared with high temperature DH and individual heating options (HP, gas and oil boilers). Technical options and barriers of LowEx approach are also tackled. An exergy evaluation has been performed using an AIT internal Matlab tool (MATLAB 2018a) based on (Favrat 2008). Results show that lowering supply temperatures increases the exergy efficiency of DH networks and consequently the whole system, also reducing return temperatures to the district heating network which increases the exergy efficiency of the system. However, one has to keep in mind when decreasing the supply temperature in the network; the water flow should be carefully considered to avoid an increase of the pumping cost.

5.3.12 CITYOPT - Study case of Vienna waste heat based micro DH

The case study of the city of Vienna/Austria involves one standard building and two low-energy buildings. The objective is to take advantage of the waste heat from a nearby industry to supply the buildings which also have their own heat source as a backup solution. The main challenges are the different supply temperatures required by the buildings and the temperature levels available from all the different heat sources involved. The second challenge is related to heat load profile and the heat supply profile, which require the use of low-temperature and high-temperature storages.

The objective of the project is to determine the best design configuration for a waste heat based micro-district heating network supplying standard and low-energy buildings. This case investigates the integration in the same network of different temperature requirements and especially low-temperatures from efficient buildings from the demand side and varying temperatures (from renewables and waste heat) and storages from the supply side.

Starting from the simulation results of the APROS tool (Pardo et al. 2015), the different scenarios and the exergy calculations were based on exergy balance equations and exergy flow equations. Results show that the low temperature storage with the booster heat pump is useful to increase the renewable share in the primary inputs, but not to improve the exergy efficiency in this case study. The analysis leads to the conclusion that from an exergetic point of view the use of more waste heat accompanied with a booster heat pump does not relate to a better overall efficiency (Pardo et al. 2015). See figure 37.

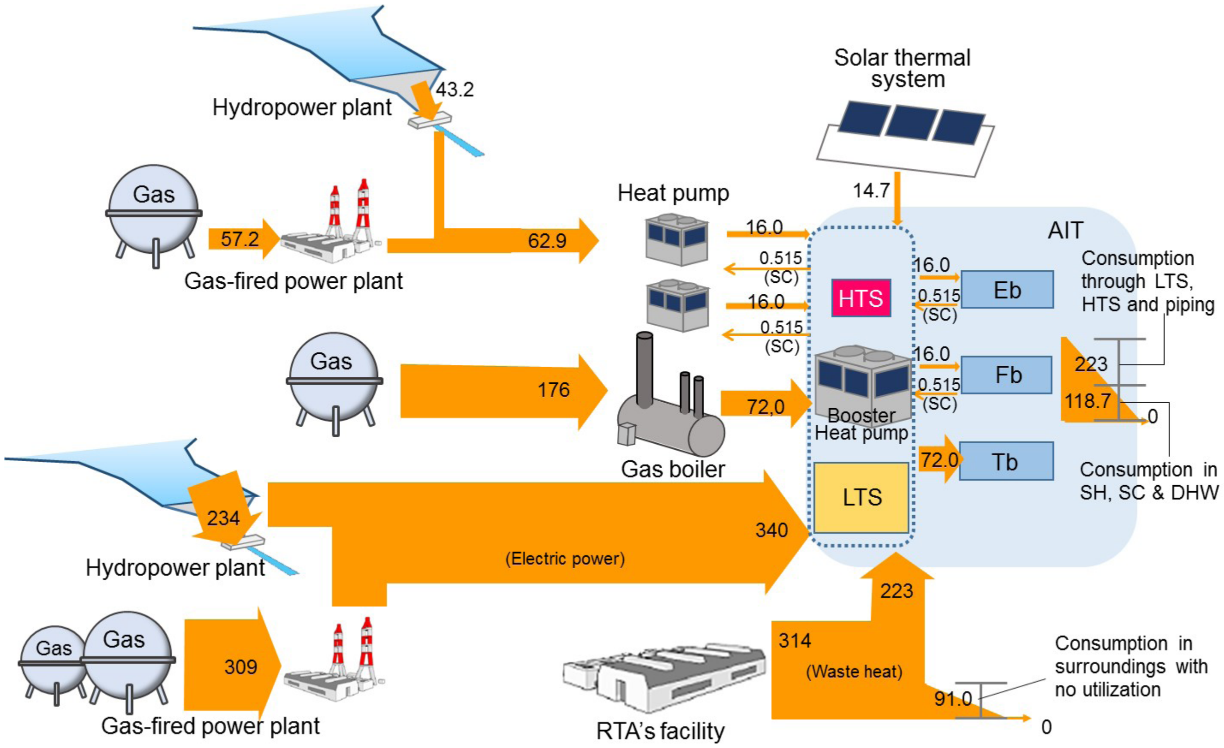


Figure 37 Exergy flow [MWh/year] in scenario indicating thermal exergy removals from space cooling.

5.3.13 Case Studies Based on the Rational Exergy Management Model and Net-Zero Exergy Districts

The Östra Sala backe project is located 2 km from the city centre of Uppsala in south eastern Sweden. The reclaimed site has triggered the need to advance concepts based on more locally available renewable energy sources as well as net-zero targets at the district level. The target for net-zero exergy districts (NZEXD) is an original target that requires the amount of energy produced on-site to be at the same grade and quality as used on an annual basis (Kilkis, 2014). This original target has been applied to the phases of the urban renewal project of Östra Sala backe to

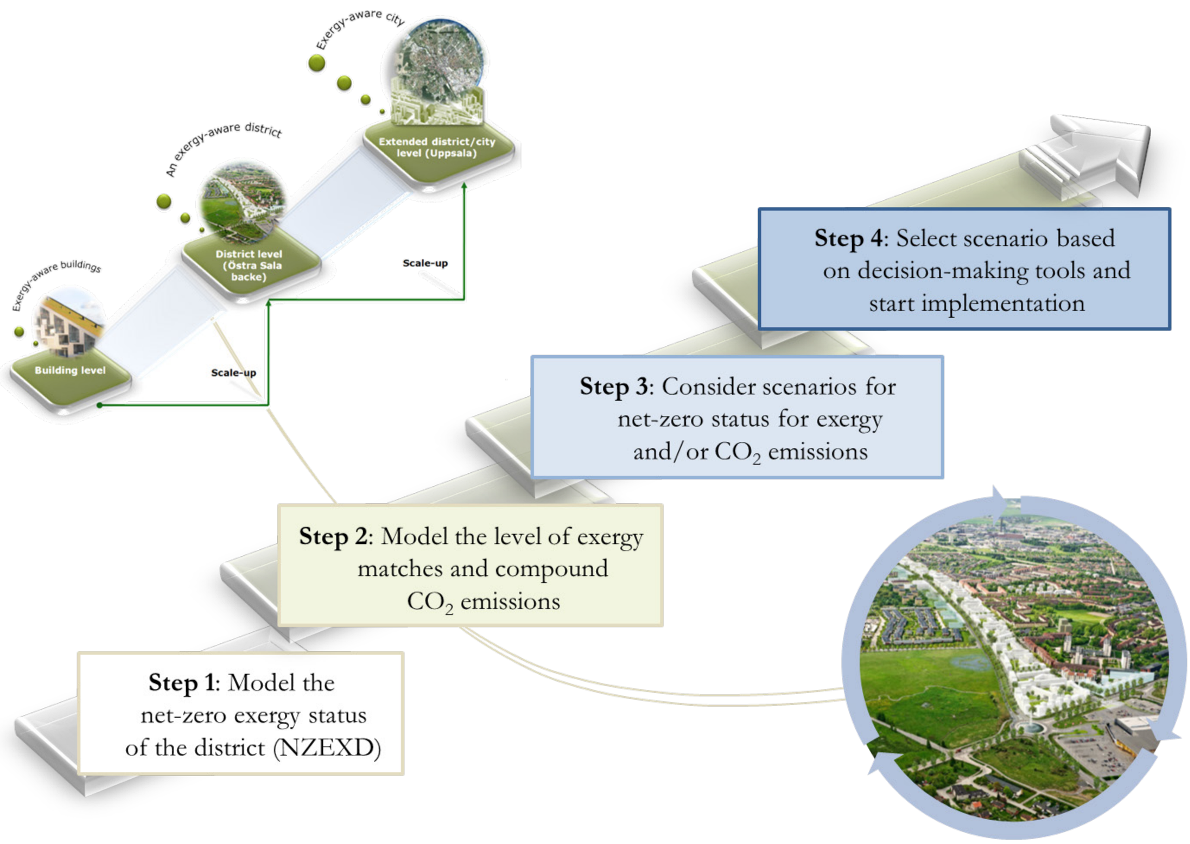


Figure 38 Four Key Steps in the Process of Planning for an Exergy Transition (Kilkis 2015).

improve the district energy system based on exergy oriented principles.

One of the main strategies to reach the NZEXD target is to plan the urban energy system in a way that will allow the district to have lower annual exergy consumption. At the same time, the exergy that is produced on-site should provide a closely matching profile to the exergy demands. These two strategies also allow the district to improve several key parameters based on the Rational Exergy Management Model (REMM), including the avoidable CO_2 emissions impact in the energy system (see 6.1.5 for the theoretical framework of REMM) (Kilkis 2011). The case study involves a fourth generation district energy system (see Figure 22).

The Rational Exergy Management Model (REMM) provides the basis to plan the components of the district energy system towards the main objective of nearing the NZEXD target. The proposal for the first phase of the district energy system is found to near the NZEXD target. For this reason, a process of exergy transition planning was further proposed and applied to the second phase. Based on the current proposal, the district will use 42.0 GWh and produce 40.2 GWh of exergy (Kilkis 2015). The comparison of the phases of the project with the supporting urban area further indicates significant improvement in an exergy per capita indicator (Kilkis, 2017).

5.3.14 Princeton University campus (global approach)

This case study consists of the Princeton University campus (New Jersey, USA) heating system with 160 buildings and a heat demand during the heating period of 2013/2014 of 132 GWh (see also 5.3.2). The demand data of the Princeton University campus heating system was provided by Princeton University, USA. Three different heat supply scenarios (including CHP and heat pump) with a supply temperature of 50 °C are studied (see 5.3.2).

The evaluation of alternatives to the current Princeton University heating system was done in order to make the heating system more sustainable. Exergy analysis is used here in order to find a system with reduced exergy destruction and exergy use.

An energy and exergy analysis was carried out using a Matlab based toolbox (Baldvinsson et al. 2016). A component based input-output analysis was applied for the exergy analysis. The results show that the initial production system can be significantly improved in terms of exergy input and exergy efficiency by replacing part of the CHP production based on gas by heat production from low-exergy sources.

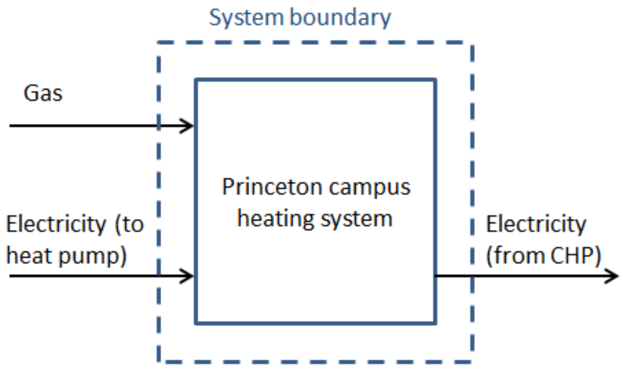


Figure 39 Boundaries of the considered system.

5.3.15 KTH University Campus

University campus building clusters of KTH-The Royal Institute of Technology (Stockholm, Sweden) can provide an effective platform for pilot energy configurations. The objective of this case study was to analyze the energy profile of a selected number of campus buildings and to consider alternative exergy-aware scenarios on the supply and demand sides.

The four scenarios with differing shares of options for cleaner energy supply structures for the campus buildings involved a comparison with a lower temperature district energy grid.

The Rational Exergy Management Model (REMM) was the main tool that was used to analyze the campus buildings. The parameters and tools of REMM are described in section 6.1.5. The reference environment temperature is taken as the reference ground temperature at 281.5 K for the Stockholm area. The scenarios indicated that savings of 16 GWh energy, 9.6 GWh exergy, and 2,663 tonnes of CO_2 emissions were possible for the building cluster based on a transition to cleaner energy supply structures. The ability to realize one of the four scenarios requires partnerships and business models that involve the public entities of Akademiska Hus and the City of Stockholm. While steps are already completed towards launching the new biofuel CHP unit, other aspects of the scenarios are dependent on decision-making processes (Kilkis 2017).

5.3.16 TU Delft University Campus

The case study involved the analysis of 28 campus buildings at the Delft University of Technology (The Netherlands) based on building level energy data for electricity, natural gas, and heat usage.The aim of the case study is to develop and apply a technique of exer-

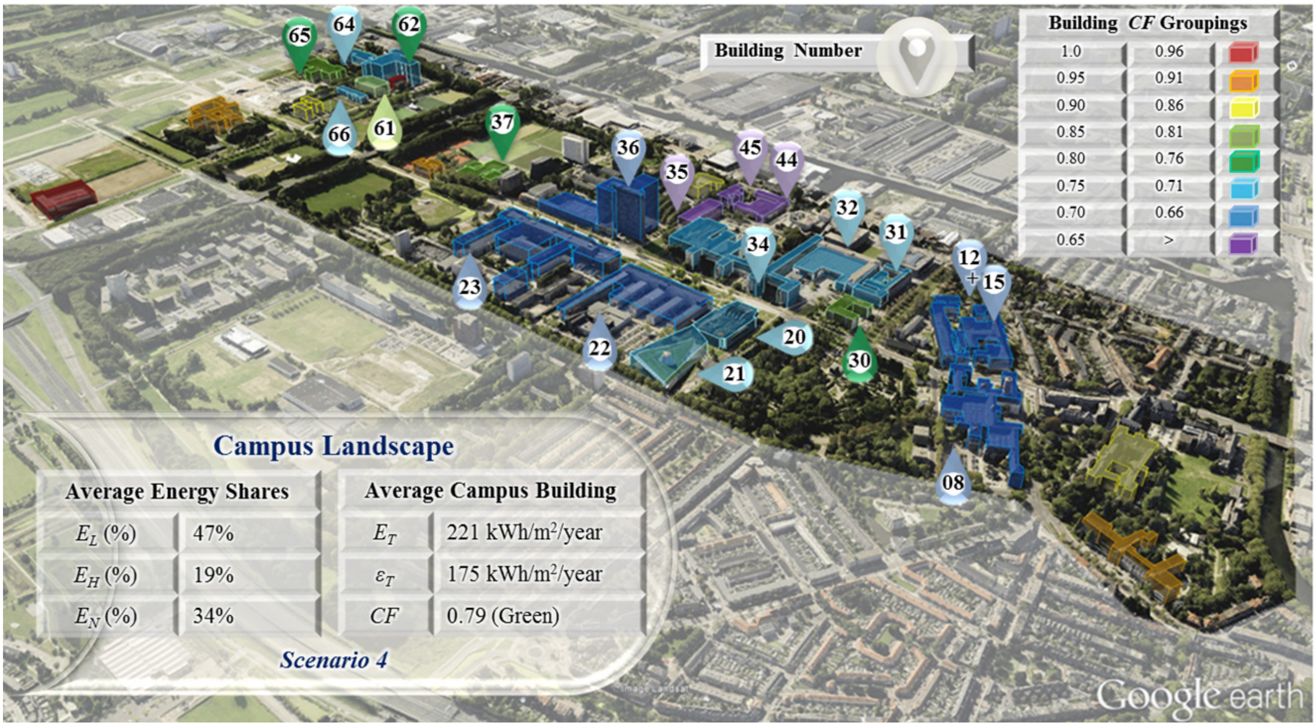


Figure 40 Mapped Results of the Fourth Scenario for Campus Buildings (Kilkis 2016).

gy scenario mapping to the largest and oldest Dutch public technological university. Such a technique supports the possibility of considering alternative scenarios with lower exergy spending as well as lower avoidable CO_2 emissions.

The scenarios are directed towards the use of lower exergy resources. For example, in the fourth scenario, a second heat distribution network with a lower supply temperature is introduced that is based on 35 % geothermal energy.

This case study represents one of the three selected case studies that were analyzed based on the Rational Exergy Management Model (REMM) (see also 6.1.5). In addition, the technique of exergy scenario mapping was developed in which the results were juxtaposed onto satellite images of the campus. The average campus building was found to use 221 kWh/m² of energy and 193 kWh/m² of exergy per year with an average Carnot factor of 0.87 in the present case. In the fourth scenario, the average Carnot factor for the campus was found to reduce to 0.79. The analysis of the case study has the potential to support the ongoing targets of the campus to reduce energy spending by 30 % and increase the share of renewable energy to 50 % by the year 2020 (Kilkis 2016).

5.4 City Scale

5.4.1 The application of BEX to the city of Halifax (Nova Scotia)

The BEX, Building EXergy model is a model developed in the PhD thesis of Baldi (Baldi 2015) with a modelling a black box approach. It uses with flexibility the available data of energy and material utilization in an urban space, and immediately and comprehensively defines the environmental impact of energy use.
The developed model is applied to a real and entire urban system: the city of Halifax, Nova Scotia Canada. A research group of Dalhousie University developed a national database of residential energy use Canadian Hybrid Residential End-Use Energy (CHREM). The objective of this case study is the application of the model BEX to the Canadian Database of residential energy use. The application of the model to a case

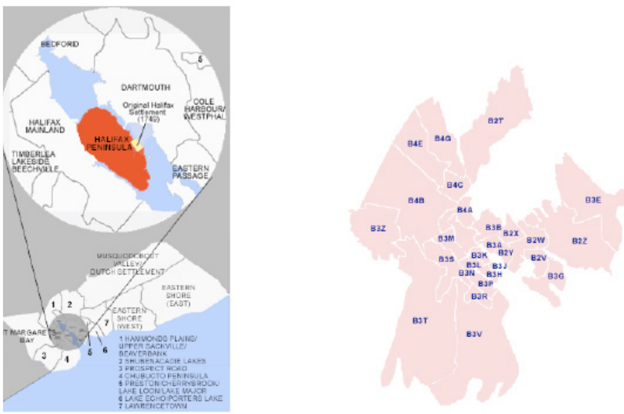


Figure 41 Location of the study area Halifax, which is in the Canadian province of Nova Scotia

study permits to evaluate the energy use scenario in order to study the application of low exergy solutions and to evaluate the exergy results.

As buildings destroy more input exergy than they lose and produce, the challenge is therefore to integrate solutions at the building and urban scale that allow reductions in irreversibility. Reducing the quality of energy sources means that the main exergy consumption is reduced. Moreover, the environmental impact from the energy use of buildings is reduced, too.

5.4.2 Energy Potential Mapping: the 3D exergy profile

Energy Potential Mapping is a method developed at the chair of Climate Design & Sustainability of the faculty of Architecture at the TU Delft, The Netherlands. The method aims to spatially quantify both energy demand, demand reduction potential and residual and renewable sources of supply. The resulting series of maps, forming an energy atlas, can then be used to shape energy and transition plans.

Because interest in the LowEx concept in the Netherlands is growing and the densely populated country has a strong tradition in spatial planning, development of a concept for expansion of the EPM method was requested by Dutch governmental agency Agentschap NL, in order to facilitate the visualisation of exergetic qualities for planning authorities in an online national heat atlas, for that reason with a focus on thermal demand. To this end, temperature ranges were defined in which both demand and supply data was categorised. The temperature ranges were chosen based on the expected levels on both demand and supply side, and because of the national focus, also included an industrial category of 110+ °C.

It should be noted that in the recently started European PLANHEAT project (Planheat 2018) in which TU Delft also participates, the temperature level ranges have been modified to below 40 °C, 40-70 °C and 70 °C and higher. The latter was chosen in relation to domestic hot water preparation requirements and related network operating temperatures, the 40 °C threshold as a minimum value with which direct heating in well insulated buildings can still be achieved without the need for separate heat pumps. Furthermore, in PLANHEAT a separate category was added for cooling, which, although not significant in the residential sector in the Netherlands, is an important category in Central and Southern Europe. Because the demand side in PLANHEAT focused specifically on buildings, industry was only included as a possible source of supply and therefore no further division of the 'high' (or 'conventional') heat range was made.

For the exergy profile, a test area was chosen in Rotterdam, on the south bank of the Meuse river, comprising five neighbourhoods (Figure 42). This area provided a range of residential blocks from different eras, as well as commercial and industrial areas.

Although the availability of georeferenced data on the building stock in the Netherlands is high and until 2018 the vast majority of houses have been heated

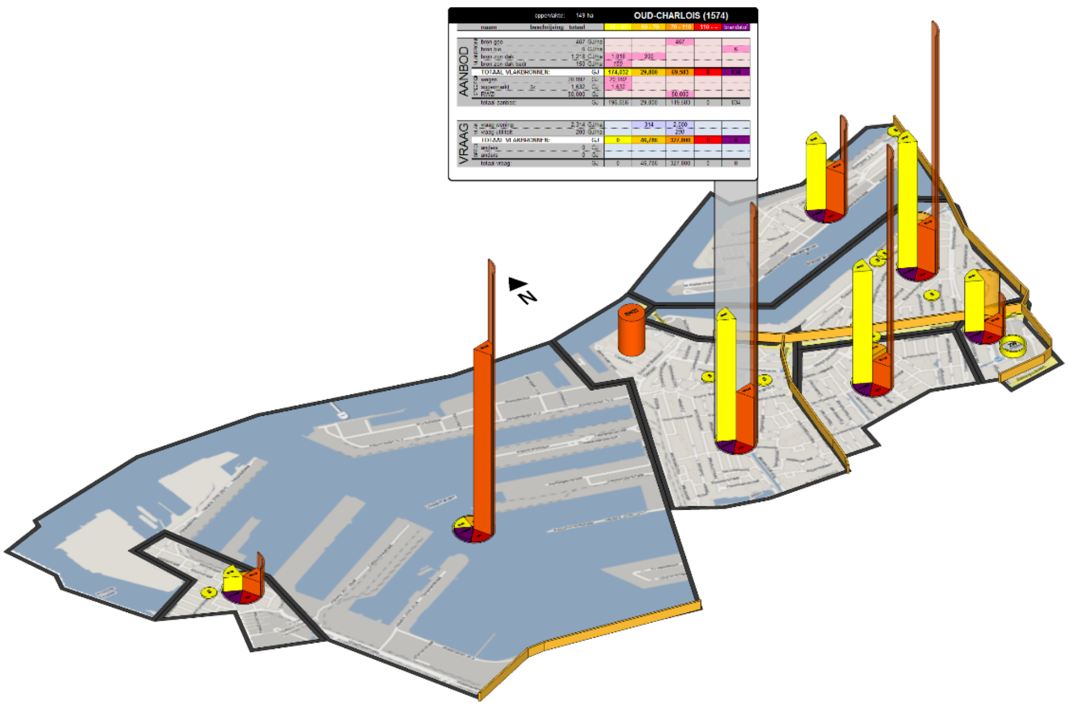


Figure 42 3D map interface showing parts of the City of Rotterdam, The Netherlands (Planheat 2018).

		oppervlakte:	618 ha	GEBIEDSNAAM (BUURTCODE)				
	naam	beschrijving	totaal	30 - 50	50 - 70	70 - 110	110 - --	brandstof
AANBOD	VLAKBRONNEN	bron geo	417 GJ/ha			417		
		bron bio	6 GJ/ha					6
		bron zon dak woning	212 GJ/ha	212				
		bron zon dak utiliteit	450 GJ/ha	*450*				
		TOTAAL VLAKBRONNEN:	**GJ**	**409.116**	**0**	**257.706**	**0**	**3.461**
	SPECIFIEK	RWZI	50.000 GJ			50.000		
		wegen	5.600 GJ	5.600				
		restw. Industrie	5.000 GJ		*5.000*			
		totaal aanbod:	GJ	414.716	5.000	307.706	0	3.461
VRAAG	VLAK	vraag woning	222 GJ/ha		40	182		
		vraag utiliteit	600 GJ/ha			*600*		
		TOTAAL VLAKBRONNEN:	**GJ**	**0**	**24.720**	**483.276**	**0**	**0**
	SPECIFI	fabriek	20.000 GJ				20.000	
		puntvraag	0 GJ					
		totaal vraag:	GJ	0	24.720	483.276	20.000	0

Figure 43 Detailed neighbourhood profile (Planheat 2018).

using natural gas, information on heat delivery systems within buildings is scarce. However, building construction years are available, and as the EPISCOPE-TABULA project later formally established, these can provide an indication of the building characteristics. The national information available on a neighbourhood level are electricity consumption, gas consumption and percentage of dwellings connected to a DH network. Based on these recent consumption figures and the age distribution of the buildings, a rough assessment was made of the expected demand temperature range for both dwelings and utility buildings. The word 'expected' is used here because the prevalence of LT and ULT heating systems is still very limited, but improved building energy standards in recent decades provide the opportunity to lower operating temperatures either directly, or after replacing delivery systems in suitably insulated buildings.

On the supply side, the thermal sources present in the city were assessed based on their expected output temperatures, the remaining source (biomass) being part of the 'fuel' category. Because the focus was on development of the visualisation method rather than perform a full study, a limited range of energy supply potentials common in the selected area was included. These included deep geothermal heat, biomass (providing the highest exergetic category, 'fuel'), roof solar thermal potential for residential and utiltiy buildings, waste heat from super markets (i.e. refrigeration based) and waste heat from sewage treatment facility effluent.

Visualisation was an extrapolation of the method used for the previously developed 3D heat map of the full city of Rotterdam for the same study, where the neighbourhood map was extruded vertically to form transparent cylinders that represented demand, and subsequently filled with layers of supply potentials. In order to simplify the increased complexity of having multiple types of demand and supply on top of the rather complex administrative borders, these were reduced to actual cylinders, projected on top of the neighbourhoods and divided up into slices that represent the different exergetic qualities.

Furthermore, details and exact figures on a neighbourhood of interest are available as an interactive pop up (Figure 43).

As with the 3D heat map, the relative sizes of the profile visualise excesses and shortages within neighbourhoods of a city and uncover exchanging possibilities in neighbouring areas. The temperature ranges additionally identify heat cascading opportunities, should sources in the right temperature range not, or not sufficiently, be available.

5.5 Business Models - Austrians district heating business model 2.0

As an example for the important integration of business models into the consideration of new energy systems design the discussion of innovative elements for urban and rural networks in Austria is presented here. Exergy efficient systems allow integrating new renewables heat sources which are often fluctuating and decentralised sources. To be able to implement these types of exergy efficient networks, appropriate business models are required. The example of the current situation in Austria within the district heating sector as a key example and its possible future evolution is given below (Geyer 2016).

5.5.1 Background to the Austrian DH situation

Currently, more than 2,400 district heating (DH) networks are operating in Austria. Besides some larger networks in urban areas the majority are small biomass bases rural DH networks. About half of the total supply is based on fossil fuels, the remaining share is distributed between waste incineration, biofuels and others (FGW 2016) – the total share of CHP is about 2/3. Due to unstable fuel and electricity prices, the long term perspective of these systems is becoming increasingly unsecure. The integration of alternative heat sources (such as solar- and geothermal energy as well as residual or ambient heat via heat pumps) can minimize investment risks, maximize the security of supply and reduce the CO_2 emissions. However, many existing systems in Austria are not designed for a significant share of alternative heat sources which are fluctuating and/or decentral and/or have a low temperature level.

5.5.2 Weaknesses of current business models

Typical business models for urban and rural DH-operators in Austria are shown in Figure 44 and Figure 45. They are based on "classical" heat distribution to the customer: heat is produced and delivered to the customers without a deep customer relationship. Moreover, the contracts are usually rigid and do not have many degrees of freedom for the customers. Having fixed and variable prices (consumed energy) is the most tariff system of DH operators in Austria. Due to (mostly) high fixed prices, customers do not see too much financial incentives for energy savings or optimization of their heating system. Although DH operators see their customers as key partners, they actually do not play a big (active) role in existing business models. Further on, DH network operators rely mainly on high temperature supply units. This is a barrier for lower system temperature and in turn prevents the transition towards the 4th generation envisaged in (Lund 2014). As a consequence, far-reaching changes (technical-ecological structural transformations) are necessary for suitable future business models in order to make greater efforts to meet customers' needs and increase the system efficiency.

5.5.3 Introducing innovative elements

Within the STRATEGO project (Magistrat der Stadt Wien 2016; Intelligent Energy Europe 2016) a coaching scheme was implemented for the two largest cities in Austria (Vienna and Graz) and two small biomass-based rural DH networks being representative for many others. In multiple coaching sessions together with Swedish partners, site visits and national workshops with local stakeholders as well as meetings with national authorities, different solution options for tackling selected key challenges in Austrian DH networks have been developed. In this framework, following innovative elements for business models in a) urban and b) rural networks have been discussed (new elements are printed in red colour and are underlined in Figure 44 and Figure 45):

a) **Urban** district heating networks: Although many urban district heating operators have their focus already on providing their customers different services and packages, the existing business models lack of financial benefits and incentives for reducing the network temperatures, integrating alternative heat sources and increasing the flexibility. Possible new elements include:

<u>Waste heat from data centres and industrial processes</u> (Figure 44: Key Partnerships 1): For the integration of alternative heat sources into district heating networks data centres offer a high potential especially in larger cities. In Vienna about 1 – 2 new data centres per year were built in the last ten years and the waste heat could be used to feed into the DH network or supply to new development areas.

<u>Reducing system temperatures</u> (Figure 44: Value Proposition 4): The long term structure of the current heat delivery contracts is a main barrier for modifications on the building side. As a consequence, customer contracts should be continuously adapted to lower temperatures if possible e.g. in new or renovated buildings. Also the compliance of the customers to the prescribed return temperatures will be more strictly pursued.

<u>Special services</u> (Figure 44: Key Activities 2): The largest customer should get a service which includes analysing heat consumption (load profile), energy savings, measures for reducing the return temperature, shaping / flattening peak loads to harmonize the profile, etc.

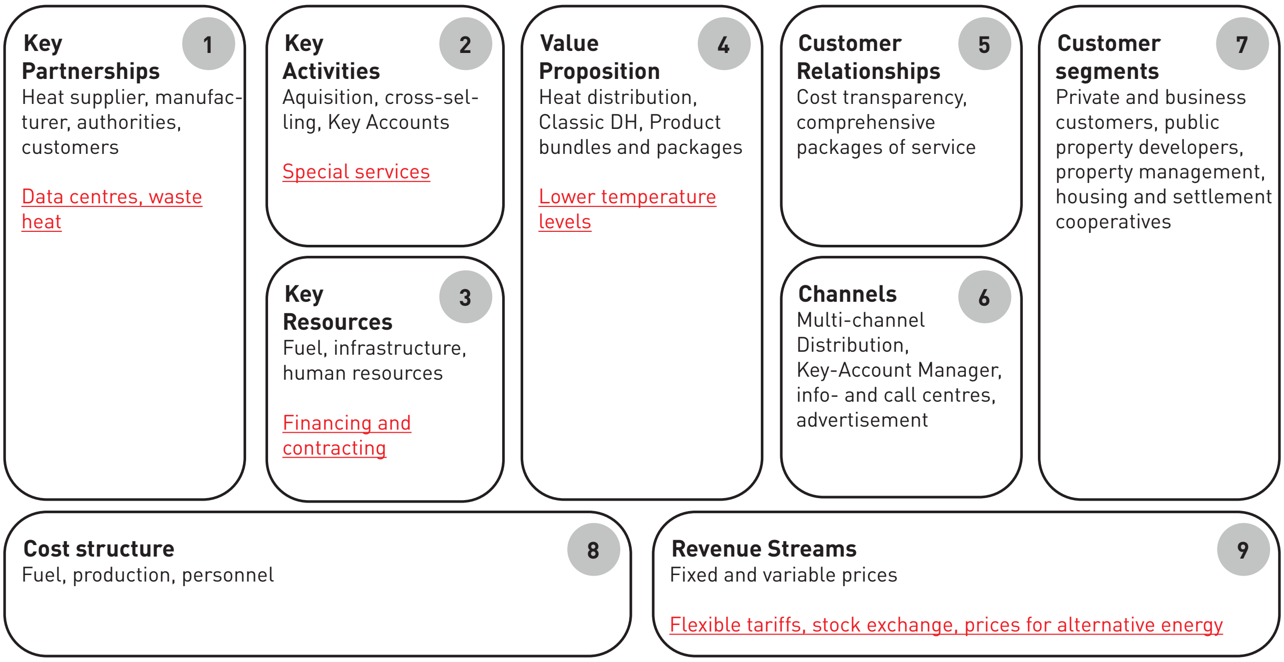


Figure 44 Typical business model for an urban DH-network in Austria (presentation from: Business Model Canvas (Osterwalder 2009); picture source: (Intelligent Energy Europe, 2016), the new elements of the business models are red underlined).

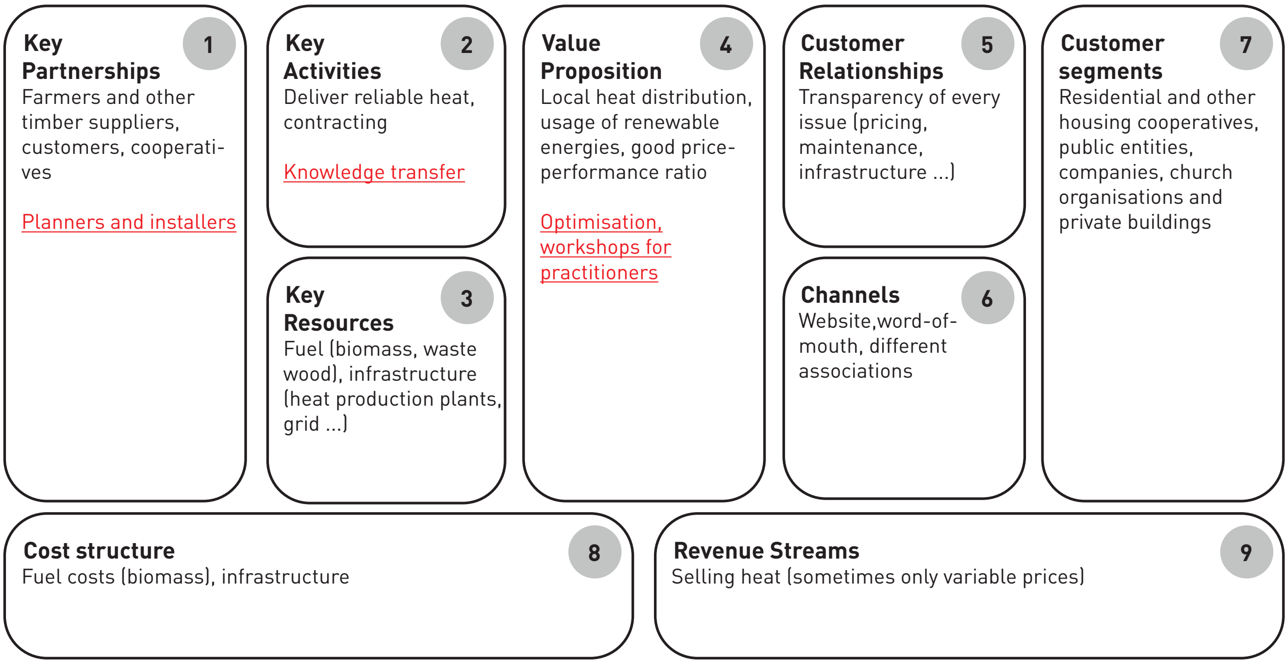


Figure 45 Typical business model for a rural DH-network in Austria (presentation from: Business Model Canvas (Osterwalder 2009); picture source: (Intelligent Energy Europe, 2016), the new elements of the business models are red underlined).

New tariff models (Revenue Streams 9):

- **Flexible tariff:** Flexible tariffs could be offered for better addressing the customer needs and to give them possibilities to influence their heating costs. New tariff models could be time dependent (e.g. daily and seasonal variations) or include a bonus/malus systems, i.e. customers could get a financial bonus for lower return temperatures. However, flexible tariff are at the current status not so easy to implement because of the Austrian weights and measures act and very often, high quality heat measurement systems with remote access are not yet extensively implemented.
- **Alternative energy tariffs:** New tariffs for alternative heat supply (e.g. solar thermal, heat pump, etc.) should be offered to the customers. The customers have the chance to select their own "green" heat supply through deciding between different energy sources with different prices. Similar models already exist for several years for electricity tariffs, e.g. "Ökostrom". Experience shows, that some customers are willing to pay higher energy bills for a more sustainable supply.

- **Experience from Sweden in implementing new tariff models shows:** The level of acceptance depends upon 1) the precision of the communication and 2) the outcome for the specific customer. Here, following customer requirements need to be considered (Sernhed 2016):
  - pay for what they consumed (variable costs)
  - transparency and easy understanding pricing
  - feel monetary effects from energy efficiency and energy saving

New financing and contracting solutions (Figure 44: Key Resources 3): For developing and implementing new business models, specialists for law, financing, contracting and other frameworks are needed.

b) **Rural** district heating networks: Many small DH networks struggle with profitability, especially during summer when the operation is inefficient and due to high heat losses because of high network temperatures. Possible new elements include:

Network optimisation (Figure 45: Value Proposition 4): One main reason for high return temperatures are faults at the substations on the customer side due to inappropriate installations and operation. Very often, planners and installers (Figure 45: Key Partnerships 1) of district heating networks in rural areas are not aware of the requirements of DH networks in connection with the installation of the secondary side respectively the consequences if they are not fulfilled. Therefore, workshops (Figure 45: Value Proposition 4) are planned to integrate the relevant stakeholders at an early stage to show them the importance of the customer side. In addition, the cooperation between different DH networks should be strengthened for knowledge transfer (Figure 45: Key Activities 2).

5.5.4 Final remarks on business models

For the implementation of innovative elements in the current business models, additional efforts are required. This is including an integrated cost-benefit analysis in order to evaluate the feasibility of the new elements and strategies for the transformation of the current business model. Here, major barriers are the organizational structures and philosophies of many companies as well as regulatory conditions and the market design in which the business model is implemented. However, the following approach for developing innovative elements of business models supporting future proof district heating networks can be described:

- Motivate the stakeholder to think "out of the box" and allow also new and creative ideas (e.g. show international best practice examples)
- Involve key partners, local stakeholders and possible new actors (such as energy contractors) to develop new business models for creating a win-win situation
- Identify the needs of the customers and allow them to take part in the development process
- Deliver a sound concept featuring economic and ecologic advantages and at the same time addressing technical and non-technical barriers

5.6 Summary and conclusions

The Low-exergy thinking can be applied to basically all systems, from one single heating component to buildings and block of buildings and very large systems such as cities or even countries. The examples presented in this chapter are scaled from buildings to cities and considers the heat and electricity domains in one system in a way that makes calculations, comparisons (between systems taken with similar assumptions) and interpretations more consistent and useful compared to the energy approach.

Exergy analysis was used through different methods and tools, further described in Chapters 3 and 6, in order to deal with various challenges such as improving the system performances in terms of sustainability and efficiency. Exergy analysis allows identifying the components or sub-systems that have potential for improvement. The case studies presented in this Chapter cover several scales and the different solutions highlighted at one specific scale can be scaled-up and scaled-down to be replicated. Exergy analysis was showed to be useful at all stages of development of an energy system: from the design phase (e.g. CITYOPT, Austria / 5.3.12) to the operating (e.g. RWTH Aachen, Germany / 5.2.1) and the renovation phases (e.g. Prêt-à-Loger, Delft / 5.2.1).

The exergy approach is until now neither popular nor extensively used for several reasons. First of all, the concept of exergy is newer and more abstract than the concept of energy as it is related to a specific system with its intrinsic constraints, boundary conditions and reference temperature. Another noticeable limitation of the exergy approach is that in order to be able to compare results, one should take care to make calculations with similar system boundaries and reference temperatures. Any comparison of uneven systems could lead to misinterpretations and biased or wrong conclusions. Indeed, as explained in Chapter 3 the input of exergy varies greatly for the chosen system boundaries of a project. The broader the system boundaries, the larger the analysis. Considering a restricted system allows focusing on specific solutions to improve the system efficiency. However, the improvement identified at a lower system may not imply better exergy efficiency if a larger system is considered. That is the reason why for instance in Case study RWTH Aachen, Germany (compare 5.2.1), the optimization algorithms investigated several system boundary conditions for different subsystems.

From the different case studies, the following points were found:

- Buildings destroy more input exergy than they lose and produce, about 84-93 % of exergy consumed by buildings is destroyed by irreversibilities.
- Exergy-based control is suitable to achieve efficient building operation. Using dynamic simulation models, the exergy analysis can be fully automatized and used for model-based control.
- The exergy analyses based on annual measurements show that ULTDH systems with local electric booster have higher exergy efficiency compared to existing DH systems.
- A low energy demand can be achieved by high buildings standard and low thermal losses among the network, wide energy share produced from renewables and good exergy efficiency, compared to traditional thermal systems.Old production systems can be significantly improved in terms of exergy input and exergy efficiency by replacing part of the heat production from fossil fuels by heat production from low-exergy sources.
- Lowering supply and/or return temperatures increases the exergy efficiency of DHN and consequently the whole system. However one has to keep in mind when decreasing the supply temperature in the network, the water flow should be carefully considered to avoid an increase of the pumping cost.
- The low-exergy approach allows identifying which component/configuration of the system to focus on, in order to implement/improve low-temperature DH networks and so to save fossil energy, having a lower overall exergy input and also reduced CO_2 emissions. By implementing ULTDH, distribution heat losses can be saved substantially.
- The exergy analysis has the potential to support strategic targets such as the reduction of energy spending and the increase of the share of renewable energy on a long-term horizon.

6 Models and tools

Modelling approaches are one of the key tools in the field of engineering. Especially in the study of energy systems, a multitude of models and tools are developed and used in both industry and academia. The models and tools which are developed for exergy analyses are introduced in this chapter along with descriptions of the reason modelling approaches are demanded for low exergy communities. As a means of answering this question, this chapter consist of two parts, collection of models and tools, and a so-called SWOT analysis of modelling approaches. Table 2 shows the list of collected models and tools, including information on the developer(s) of each model.

Table 2 List of regarded models and tools

	Abbreviation	Full name, Developer (names, institute, country)
1	OLEC	Optimization of Low-Temperature Cluster Eric Willems, Adnan Dedeoglu, Peter Op't Veld, Huygen Consulting Engineers BV, The Netherlands
2	LowEx:CAT	Low Exergy Cluster Analysis Tool Anna Marie Kallert, Fraunhofer IEE, Germany
3	GICOP-DHS	Geographic Information-based Cost Optimal Planning of District Heating System Ivar Baldvinsson, Austrian Institute of Technology, Center for Energy, Austria
4	MODEO	Multi-Objective District Energy Optimisation Cong Wang, Ivo Martinac, Alessandro Magny, KTH Royal Insitute of Technology, Sweden
5	REMM	Rational Exergy Management Model Siir Kilkis, The Scientific and Technological Research Council of Turkey, Turkey
6	CARNOT	Conventional And Renewable eNergy systems Optimization Toolbox Solar Institut Jülich, Germany; Paul Michael Falk, Frank Dammel, Institute for Technical Thermodynamics, TU Darmstadt, Germany
7	BEX	Bulding EXergy Model Marta Giulia Baldi, University of Florence, Italy
8	ULTDH	Ultra Low Temp District Heating Xiaochen Yang, Svend Svendsen, DTU, Denmark
9	DEH	District Electrical Heating Maria Harrestrup, Xiaochen Yang, Svend Svendsen DTU, Denmark; Klaus Lund Nielsen Danfoss A/S, Denmark
10	ExEx	Exergetic and Exergoeconomic Analyses G. Tsatsaronis (among others) TU Berlin, Germany. Applied within Annex 64: Frank Dammel, Paul Michael Falk, TU Darmstadt, Germany
11	DyEx	Exergetic and Exergoeconomic Analyses G. Tsatsaronis (among others) TU Berlin, Germany. Applied within Annex 64: Frank Dammel, Paul Michael Falk, TU Darmstadt, Germany

12	DEA	Dynamic Exergy Analysis Tool Roozbeh Sangi, Marc Baranski, RWTH Aachen University, Germany
13	RS4DEA	Reference State for DEA Saeed Sayadi, Technische Universität Berlin, Institute for Energy Engineering, Germany
14	SPM2.x	Stochastic Profile Maker 2.x Anna Marie Kallert, Fraunhofer IEE, Germany

6.1 Collection of Methods, Models, and Tools

During the course of the EBC Annex 64 project in total 14 tools have been identified and are presented and analysed in the following (see also Appendix C: Additional information on Tools and Models):

6.1.1 Optimization of Low-temperature Cluster Grids in Districts (OLEC)

Optimization of Low-temperature Cluster Grids in Districts (OLEC) is a tool that aims for the energy transition to gain understanding of trade-offs in energy infrastructure based on the principle of local hybrid energy infrastructures for utilization of locally available sustainable, low-value energy sources and energy storage.

The tool is a set of simplified and advanced models that starts with the mapping of the time-dependent energy supply and demand profiles in the built environment in which the basic principle is that buildings need only low-value energy for heating. It makes use of the convergence of hourly energy profiles in larger districts from 500 dwellings and more. Furthermore, the built environment is classified in reference districts to simplify first time assumptions in a quick scan modelling. In addition, there is an inventory of the possibilities for storage systems in the underground or in large tanks. This reflects also the necessary planning tools to quickly and efficiently gain insight in low-temperature heating networks and grid storage systems, based on the interaction between building, supply and storage. With these tools is a catalogue of 'preferred configurations' (presented in a catalogue) for different combinations of properties/sources, users/buildings as well as possibilities for modular expansion and scaling up (smart planning). Besides the quick-scan catalogue a detailed grid-model is under development, named CHESS that can handle hourly data entries from the energy demand profiles and the waste heat supply to be predefined by the user according to the waste heat source properties (Willems Claessen 2017; Koene et al. 2004).

These energy models come also with detailed financial models to arrange financing and evaluating financial risks for supply contractors for these heat grid solutions.

6.1.2 LowEx:CAT - Low Exergy Cluster Analysis Tool

The simulation tool the "LowEx:CAT, Low Exergy – Cluster Analysis Tool" was created as part of the PhD- research project "Modelling and simulation of low-temperature district heating systems for the development of an exergy-based assessment method" (Kallert 2018). The investigations as part of the model are aimed at the comparison and evaluation of different energy supply strategies based on low-temperature district heating (LTDH) technology. The assess-

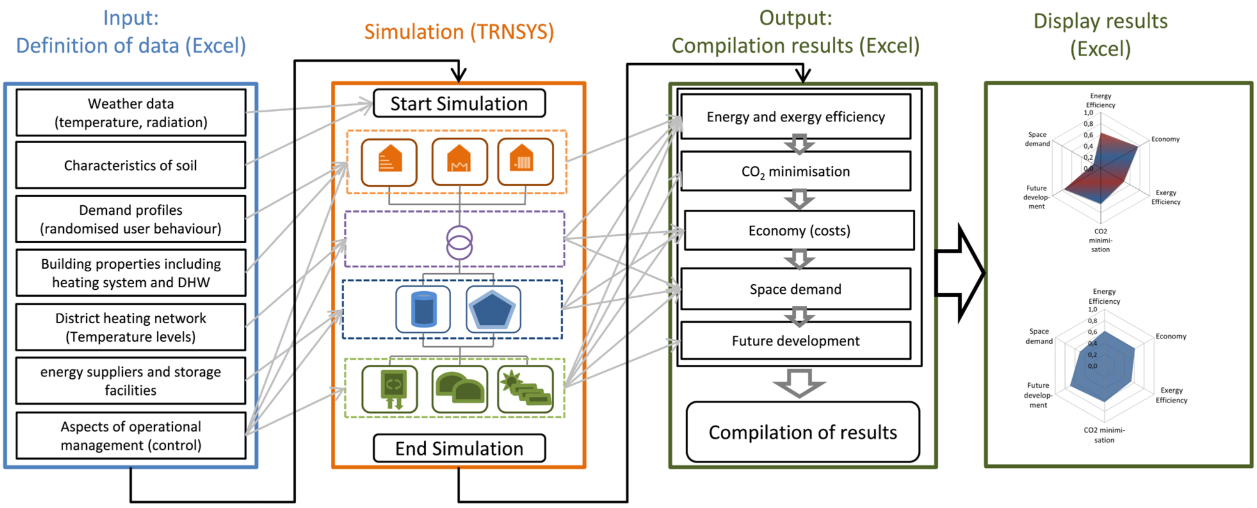


Figure 46 Main working principle of the assessment using the model "LowEx:CAT" (Kallert 2018).

ment aims towards a comprehensive, exergy-based evaluation of renewable-based LTDH supply schemes by using approaches of multi-criteria analysis. For the evaluation of LTDH supply, the exergy analysis is applied and combined with additional evaluation parameters. These parameters comprise energy efficiency, greenhouse gas emissions, full cost analysis as well as space requirements and the flexibility in future energy systems.

Figure 46 shows the main principle of the assessment by using "LowEx:CAT". The main process steps are "input", simulation" and "output". As part of "input" the input data (e.g. characteristics of the buildings and supply system or weather data) are defined and read in by "Simulation". "Simulation" is the 'engine' for dynamic calculation by using TRNSYS (TRNSYS17 2014). As part of "Output," all the results are assessed by using an Excel-tool according to defined solution variables (Kallert 2018; Kallert et al. 2017).

With the tool both groups of new buildings and existing buildings can be evaluated. By using the model technological advantages, challenges and barriers of different supply technologies can be identified. However exergy assessment as a sole evaluation method highlights the potentials of innovative LTDH supply solutions on a sound thermodynamic basis. In this way an important contribution can be made for increased efficiency of energy supply and the transparency in the comparison of supply alternatives.

6.1.3 GICOP-DHS (Geographic Information-based Cost Optimal Planning of District Heating System)

This model provides a cost optimal district heating system design and operation, based on a geographic information, multi period and deterministic mixed integer linear programming (MILP) model. It presents cost optimal distribution network structure and optimal capacity and dispatch of different heat supply units of a district heating system, by minimizing the annualized investment and operation costs of the system. A network topology of nodes and edges, providing accurate geographic representation of the district, is generated using a geographic information system and acts as a model constraint. System components such as centralized and distributed heat supply units are fed exogenously to the model according to the wishes of the user, forming a model superstructure along with the network topology, representing possible connections of consumer nodes, supply nodes and network edges. The model is formulated as a set of linear algebraic equations representing component interaction and system design and operation behaviour. The objective function to be minimized represents the annualized total investment cost of system components over their respective economic lifetime, as well as the annual operational cost. The model has been formulated in GAMS (General Algebraic Modelling System) and executed using the CPLEX solver. The advantage of the model is the disaggregated and accurate district heating network presentation which allows for thorough cost and operation analysis of the network and consideration of temperature and hydraulic requirement of consumers, rather than relying on empirical values (Baldvinsson et al. 2016).

6.1.4 Multi-Objective District Energy System Optimization (MODEO)

This model serves as a tool for the optimal design of energy supply systems for building clusters and districts. The model addresses aspects of energy performance, environmental performance, economic performance, and exergy performance, through a multi-objective optimization approach. A wide range of energy conversion technologies and energy sources including both renewables and non-renewables have been modelled. As part of the model, all the objective functions are calculated by an in-house MATLAB script (MATLAB (2018a) that models and simulates the energy system. The optimization results are presented in the form of Pareto fronts (see Figure 47), through which decision-makers can understand the options and limitations more clearly and ultimately make better and more informed decisions (Wang et al. 2016).

6.1.5 The Rational Exergy Management Model (REMM) and Related Analysis Tools for Net-Zero Exergy Districts

The Rational Exergy Management Model (REMM) was developed as an analytical model to assess the level of match between the supply and demand of exergy as a means of determining the avoidable CO_2 emissions impact in the energy system. The model considers the primary energy spending that can be avoided across multiple sub-systems in the energy system through better exergy matches at the building, building cluster, campus, district, and/or city level. In this respect, the model utilizes an energy systems perspective with the objective of improving exergy matches and reducing avoidable CO_2 emission impacts. The stepwise approach of applying the analytical framework and the intra-systems boundary of analysis provides a means to improve the rationality of resource usage in the energy system to curb CO_2 emissions (Kilkis 2011).

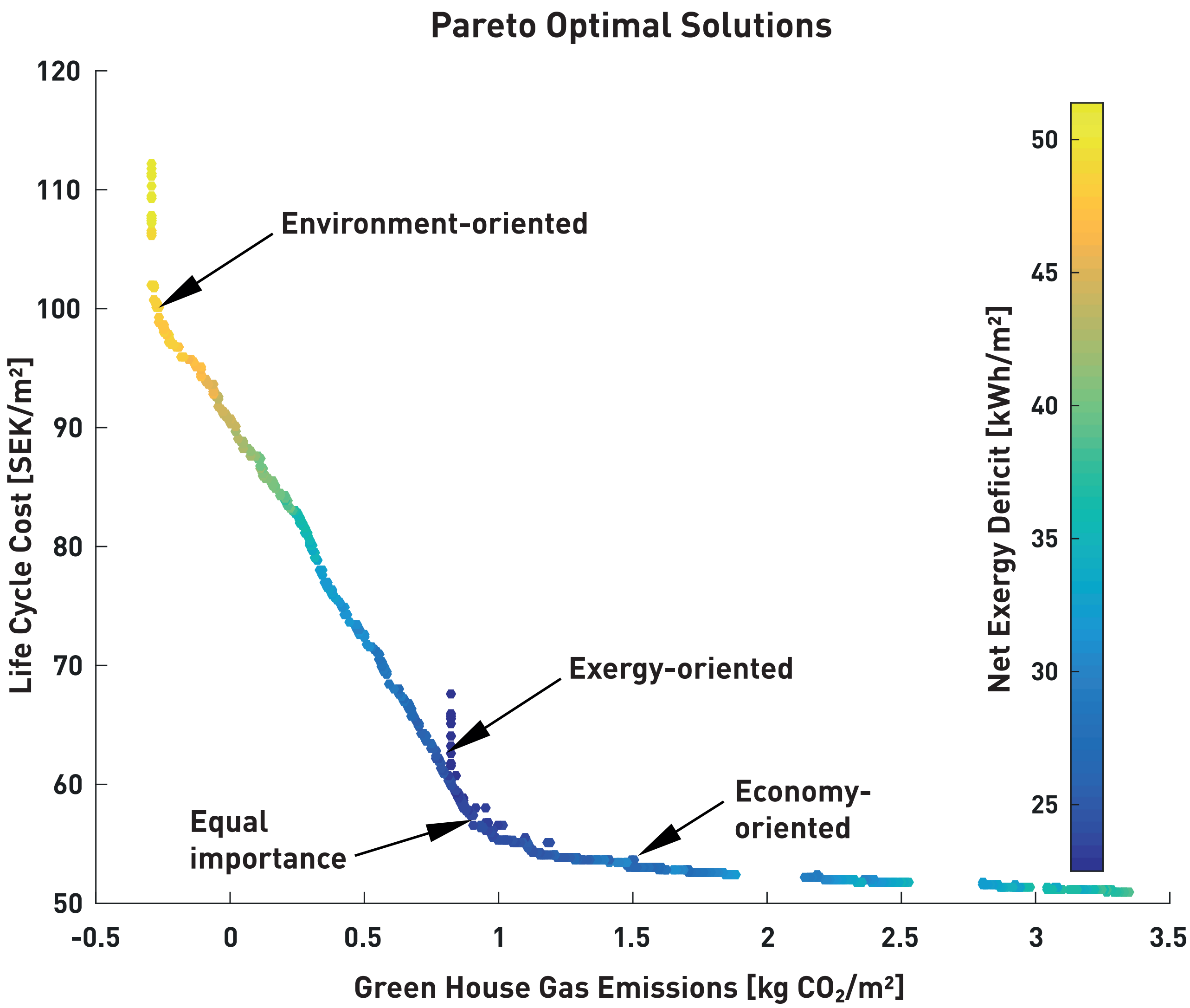


Figure 47 Example for Pareto fronts to support decision-makers to understand the options and limitations

REMM was further utilized to improve the status of districts in an original net-zero target based on exergy, namely, the target of a Net-Zero Exergy District (NZEXD). NZEXD is a district that produces the same amount of energy at the same grade and quality as used on an annual basis. Principles based on REMM are used to guide districts in reducing the amount of exergy that is consumed in a given year and to increase the amount of exergy that is produced on-site. To date, the model has been applied to assess the present case and scenarios for various cases in the built environment, including building clusters at KTH – The Royal Institute of Technology (Stockholm, Sweden) (see 5.3.15), the campus of TU Delft (Delft, The Netherlands) (see 5.3.16), the Albano district (Wang et al. 2016), the district heating system of the city of Stockholm as the first European Green Capital, and proposals for the Östra Sala backe district in Uppsala Municipality, Sweden (see 5.3.13). In the latter case, the phases of the Östra Sala backe district project were used to develop a stepwise approach to propose an improvement in the NZEXD status and to enable decision-makers to undertake a transition planning framework. The stepwise approach was supported by a REMM Analysis Tool for Net-Zero Exergy Districts that was developed to provide the opportunity of evaluating the phases of a project, including through a Net-Zero Exergy District Option Index.

The REMM model and related analysis tools for the NZEXD target support the scope of Annex 64 to demonstrate the benefits of exergy-oriented approaches to increase renewable energy utilization, reduce CO_2 emissions, and obtain more sustainable energy systems. As summarized in Figure 48, analyses based on REMM can enable the effective use of exergy principles to contribute in identifying strategies towards CO_2 mitigation by directly addressing deficits in exergy matches through an energy systems perspective. Moreover, districts and urban settlements can benefit from restructuring the urban energy supply and demand structure to reduce the need for high exergy resources and increase on-site production from renewable energy sources towards reaching net-zero targets based on exergy and lowering avoidable CO_2 emissions impacts.

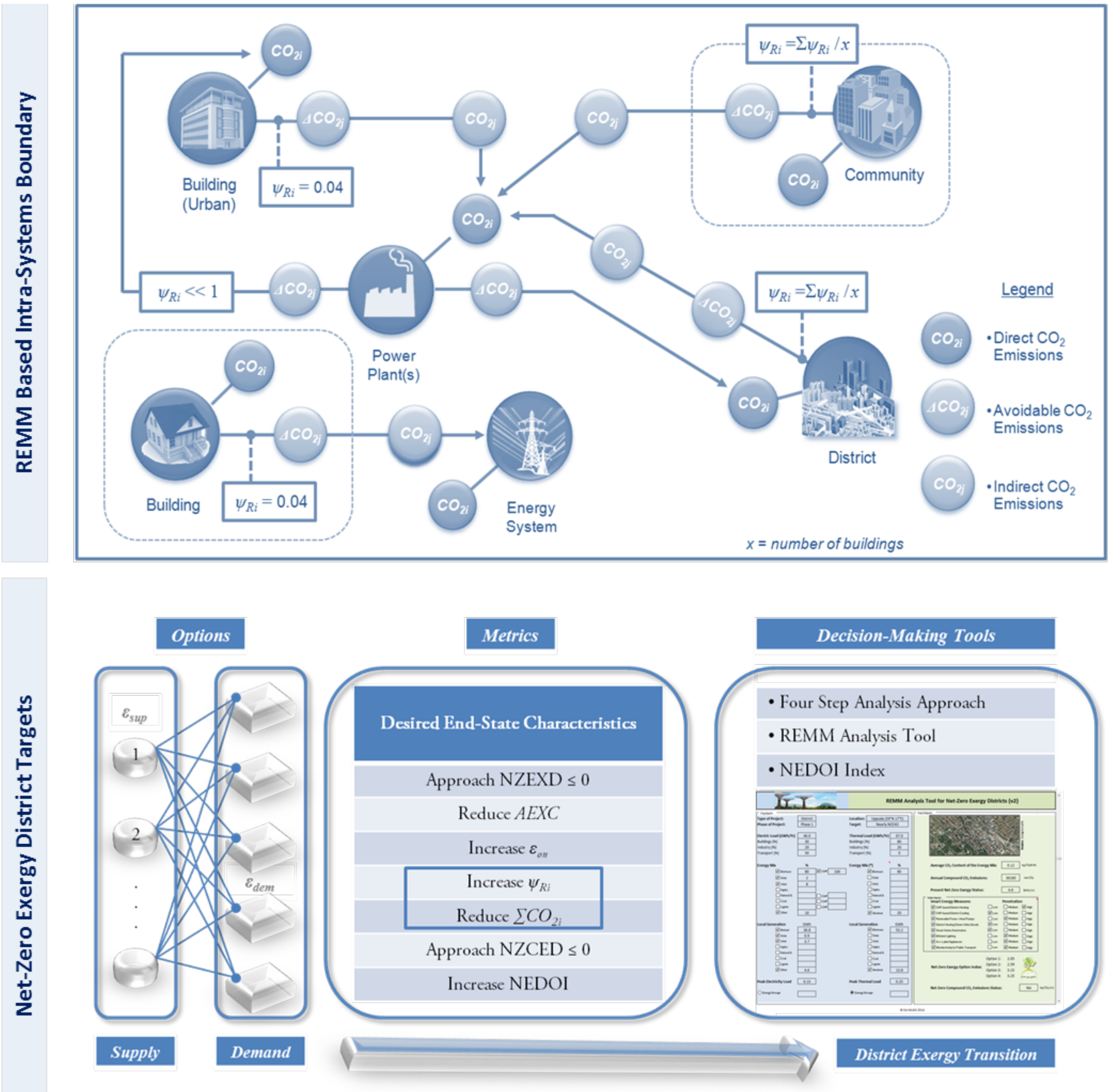


Figure 48 Overview of the Rational Exergy Management Model and Related Targets (Kilkis 2015)

6.1.6 CARNOT - Conventional And Renewable eNergy systems Optimization Toolbox

CARNOT (Solar Institut Jülich 1999) is a MATLAB/Simulink based toolbox (MATLAB 2018b) which allows for the simulation of heating systems via predefined components in a library. It is structured in block sets which helps visualizing the modelled system. Through its open code concept, all components can be modified and adapted by the user. For all components detailed descriptions and information are given in the manual. New components can be implemented via embedded MATLAB functions so that the use of CARNOT is not limited to the existing library. Real and generic studies can be conducted with CARNOT, since it is possible to use real data in form of time series as well as simulated buildings within the model. Exergy calculation is not yet part of the library, but can be easily included in CARNOT. CARNOT is a suitable tool for researchers as well as planners.

6.1.7 BEX Model – Building EXergy Model

The developed model applies the Second Law of Thermodynamics (Moran and Shapiro 2004) to a building focusing on the interactions with the environment at the borders of the system. The model aim consists in the computation of the amount of energy a building uses and the quantity of exergy it produces, consumes and loses degrading the quality of energy. Since it is focused on the thermodynamic flows on the system boundary, it does not require an observation of the system behaviour through a Second Law balance. In particular, an exergy balance would not exist for the real processes if a quantity exergy destruction ExD is not introduced: it is because a portion of the input exergy is always destroyed by irreversible entropy generation. The model determines an exergy balance of a system: the time step of energy and exergy analysis have to be chosen considering the shortest time period required to obtain a meaningful variation of the boundary properties. The model structure is very similar to that of a standard energy analysis. In comparison to energy (internal energy is a function of the state of the considered matter only), exergy is a function of the state of the considered matter and of the common components of the environment. The model is a tool to link the building to the territory in terms of exergy. Each building continuously utilizes and converts energy and uses materials, consuming exergy. As the energy balance model, the exergy balance model becomes more significant in the implementation and comparison of different energy/exergy saving measures. The traditional energy saving measures are different from exergy saving measures: the model is useful to compare them. Two are the contributions over the previous model. The first one regards the model approach: it considers the building as a black box. The information about the internal energy transformation is not considered at steady state conditions. The second one concerned the choice of the reference state: the model uses the transient surrounding air and not the fixed temperature as traditional. Both these aspects are discussed in a previous section. The model at the same time includes the thermodynamic interactions, energy and material fluxes, between the building and the surroundings: surrounding air, surrounding ground and water supply. The building is considered as an open thermodynamic system, it is defined by the control volume (Baldi 2015; Baldi and Grazzini 2016).

6.1.8 Using ground water for ultra-low temperature district heating in Bjerringbro City for heating and cooling

The Bjerringbro district heating company (Denmark) supplies heat to ultra-low temperature district heating (ULTDH) customers with supply temperature at 46 °C. Ground water is used to cover the cooling demand of the company Grundfos buildings during summer and the heated ground water is recharged and used for district heating during winter. A ground source heat pump (GSHP) unit is used as heat supply to produce district heating water at 46 °C and 67 °C to different areas. A cogeneration plant and a heat plant are supplemented for the peak load. Considering that the heat carrier at 46 °C may be insufficient to guarantee the comfort and hygiene requirements for domestic hot water supply, electrical supplementary heating devices are installed locally. It is assumed that, the domestic hot water is heated to 45 °C by electricity on the customer side, and the indoor temperature heated by space heating is 20 °C. The boundary for exergy analyses was limited to the ULTDH area only. To give a more clarified insight of the performance of ULTDH, two other artificially DH systems were built for comparison: ULTDH system supplied by CHP/ heat plant (high temperature heat sources); 70/40 °C DH system supplied by CHP/heat plant (no local electrical supplementary heating) (Gong and Werner 2015; Li et al. 2014).

The exergy utilization rate ζ were investigated as the indicator for the system exergy performances. In addition, energy and economy performance are also investigated (see Figure 49).

6.1.9 District Electrical Heating utilising the building thermal mass and predictive control (DEH)

This method demonstrates a solution for heating nZE-Buildings (nearly zero energy buildings) with surplus off-peak electricity, where it has not been connected to the district heating grid. At midnight the space heating demand is predicted for the upcoming day based on weather forecasts (solar radiation and outdoor temperature). The aim is not to become more energy-efficient, but to use surplus renewable electricity (low "quality") during night time instead of electricity during daytime (high "quality"). The hypothesis is that: A nZEB can be heated with surplus electricity during off-peak-hours (00:00-06:00) by storing electricity as heat in the concrete floor construction, where it will

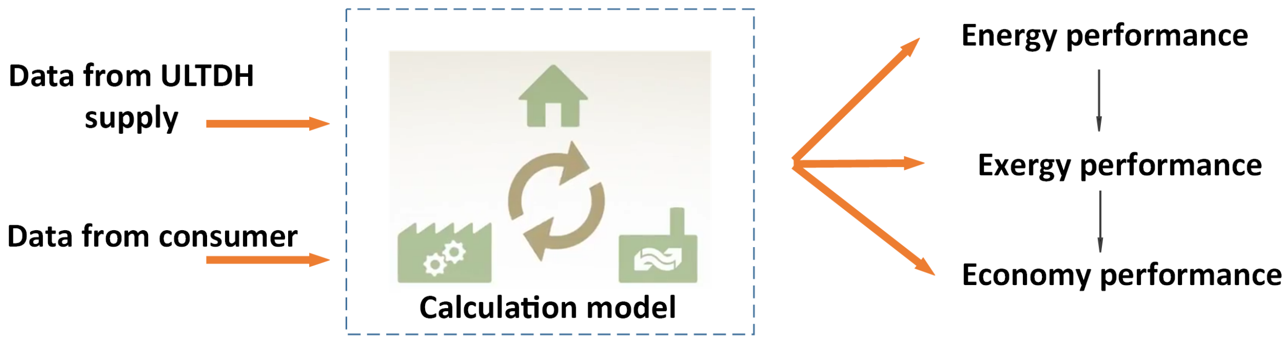


Figure 49 Structure of the ULTDH model

be released during the next day, providing sufficient space heating without causing thermal discomfort at any time. A nZEBuilding has been used as case and measurements have been executed during February 2016. A simulation model of the test building was built in IDA ICE (IDA ICE (2018). Whether the thermal comfort can be achieved by such operation was tested by IDA ICE model dynamically. Moreover, different scenarios were made to investigate the boundaries of applying this concept. Exergy performance of the predictive controlled electrical heating was analysed by using the real measurements from the test building (see also 5.3.7) (Harrestrup et al. 2016).

6.1.10 Exergetic and Exergoeconomic Analyses

An exergoeconomic analysis is a combination of an exergy analysis and an economic analysis (Figure 50). The objective is to get an overview of all costs contributing to the overall costs related to the desired output ("product") of a system. It is possible to identify the components, at which – from an economic point of view – an improvement could be most beneficial. Additionally, an optimization of the structure and the mode of operation of a system is possible (Tsatsaronis 1993; Tsatsaronis 2007).

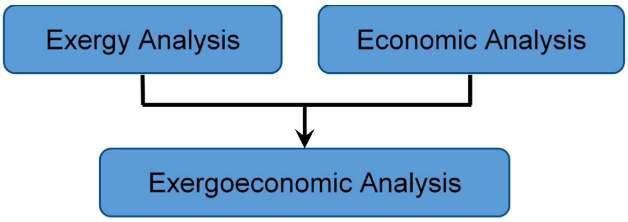


Figure 50 Approach to the exergetic and exergoeconomic analyses

Specific costs are assigned to exergies entering the system under consideration ("fuel exergies"). Additionally, costs are assigned to each component of the system. This approach results in costs for all exergies transferred within the system and out of the system ("product exergies"), directly linking exergy destruction with costs and showing improvement potential.

The general procedure of exergoeconomic analyses is described using the example of a simple heat pump consisting of a compressor, a throttle and two heat exchangers (Figure 51). A model for the system under consideration is derived and the exergy flows are determined. Specific costs are assigned to exergies entering the system. In the heat pump example, exergy enters the system in form of electricity that powers the compressor. For all components costs for purchase, operation and maintenance are needed. Results are the cost flow inside the system and the costs for the output ("product") in form of the discharged heat flow at the upper temperature (Lazzaretto and Tsatsaronis 2006).

6.1.11 Dynamic Exergoeconomic Analysis using Monitored Data

An exergy analysis provides desired information about the thermodynamic performance of a system and its components. Therefore, a system can be analysed, and consequently be improved from the thermodynamic point of view through an exergy analysis. However, there is a lack of information about monetary losses associated with exergy destruction (i.e. the thermodynamic inefficiencies). An exergoeconomic analysis provides effective assistance in identifying, evaluating, and reducing the thermodynamic inefficiencies and the costs in a thermal system. It improves our understanding of the interactions among system components and reveals opportunities for design improvements that might not be detected by other methods. A complete exergoeconomic analysis consists of an exergy analysis, an economic analysis and an exergy costing. For building applications, since an exergoeconomic analysis in most of the cases will be applied to an already-existing building and its HVAC systems, there will be no need to take equipment costs into account. This means only an exergy analysis and exergy costing would be sufficient, without an economic analysis. This is not true when the design of a building and the selection of its HVAC components are considered for a new system. In this situation, an

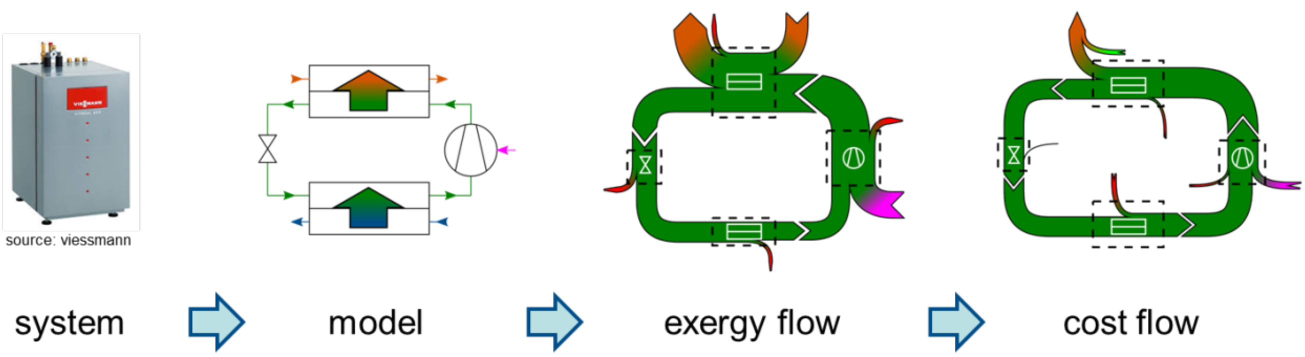


Figure 51 Example for exergoeconomic analysis of a Heat Pump ch to the exergetic and exergoeconomic analyses

economic analysis is necessary to find the optimal size and type of system components, as well as the optimal building design. In the present work, it is assumed that the building and its energy systems already exist. Thus, the capital investment and operating and maintenance (O&M) expenses are not included in the analysis. The intention of conducting an exergoeconomic analysis for a building envelope in this study is, in fact, not to change the system configurations, but to analyze and improve its operation (Tsatsaronis 2007; Lazzaretto and Tsatsaronis 2006).

6.1.12 Dynamic Exergy Analysis Tool for HVAC systems (DEA)

To perform the exergy analysis of building energy systems systematically, there is a need to develop a methodical approach, otherwise exergy equations need to be written for each single component of all case studies. The concept of object-oriented programing has been applied to develop a tool for the dynamic exergy analysis of HVAC systems suitable for a wide range of components. The exergy analysis tool has been developed in the equation-based, object-oriented programing language Modelica (Modelica 2018). The reason behind using Modelica as the modelling language is that Modelica is powerful language to dynamically model thermohydraulic systems. The existence of broad and established component libraries is a further advantage.

The task to perform a dynamic exergy analysis of an energy system is divided into two parts, which is conducted by two sub-models, the ExergySensor and the ExergyAnalysisTool. The ExergySensor collects required data from the system that is to be evaluated and calculates exergy fuel, product and destruction for each component. To perform a dynamic exergy analysis, multiple models of the type ExergySensor are placed in the system under consideration, one per component being analysed. The auxiliary variables calculated in the ExergySensor of all components are forwarded to the ExergyAnalysisTool, where the exergy benchmarks, namely exergy efficiency ε, exergy destruction ratio y, relative irreversibility RI and improvement potential IP are calculated. The ExergyAnalysisTool is publicly available as a package in the open source library AixLib, which is a Modelica model library for building performance simulations. Figure 52 shows the working mechanism of the tool and interaction between a component, the ExergySensor and the ExergyAnalysisTool (Baranski et al. 2016; Sangi et al 2014).

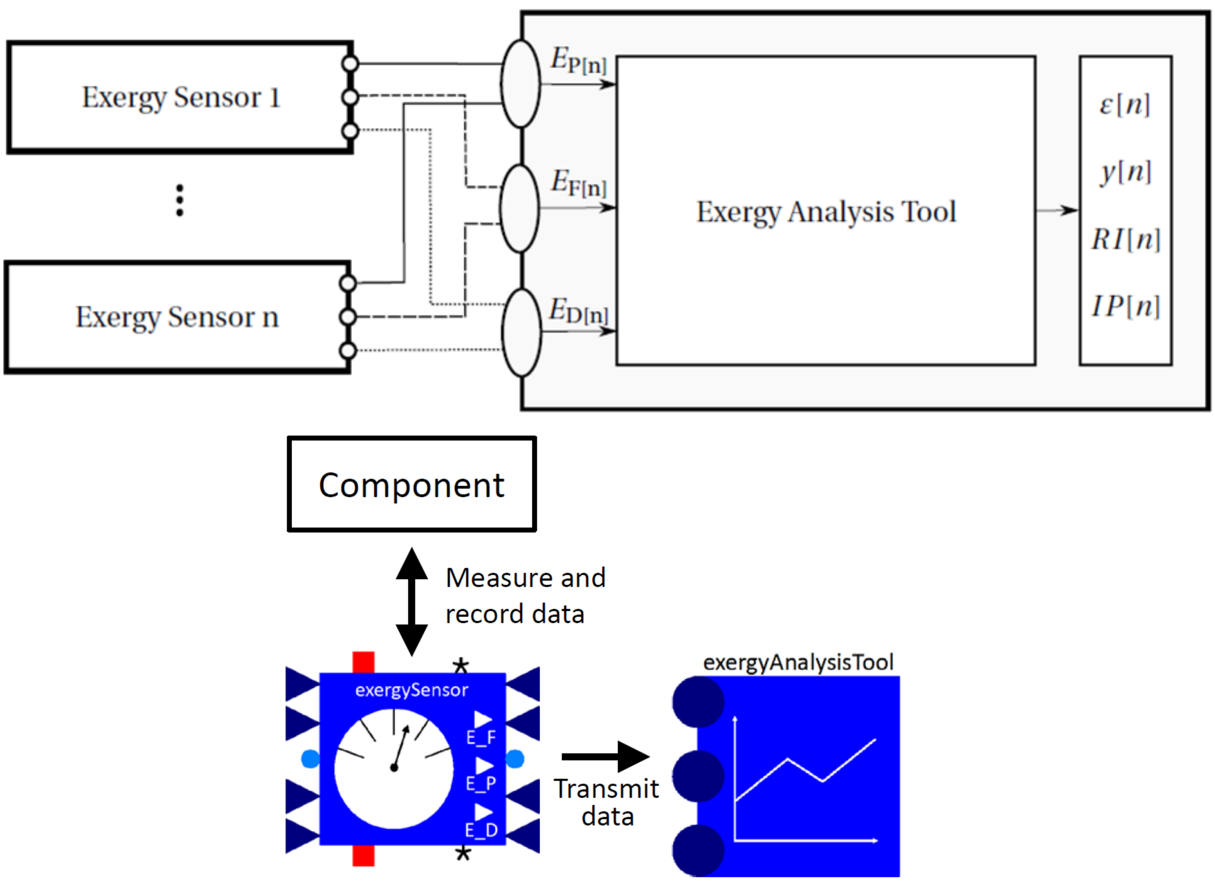


Figure 52 (Top) Working mechanism of the tool. (Bottom) Structure of the model and interaction between a component, the ExergySensor and the ExergyAnalysisTool.

6.1.13 The Reference State for Dynamic Exergy Analysis

Definition of the reference state is a principal issue in an exergy analysis. When the state of a system is extremely different from that of the reference state, variations in properties of the reference state do not influence the results of an exergy analysis significantly (e.g., in power plants). On the contrary, when properties of a system are close to that of the reference state, results of an exergy analysis undergo strong variations depending on the definition of the reference environment. This corresponds to the case of applying an exergy analysis to the heating and cooling systems in buildings; especially if their temperature levels are close to the ambient temperature (i.e. LowEx systems) (see also Torio and Schmidt 2011).

The majority of studies in the literature follow a steady-state approach to conduct an exergy analysis. The reference temperature, therefore, can be chosen as a fixed temperature such as the seasonal mean temperature, the annual mean temperature and the design temperature. In fact, there is no common agreement on a proper definition of the reference environment for a steady-state analysis. On the other hand, accurate estimations for energy and exergy flows in buildings are obtained only through a dynamic analysis. Several possible reference temperatures are proposed for a dynamic exergy analysis: (1) the universe temperature, (2) the indoor air temperature, (3) the undisturbed ground temperature, and (4) the outdoor temperature. The latter one has been widely used as the reference temperature in a number of studies. However, due to the fluctuations in the ambient air temperature, the exergy of each stream in a system, as well as the exergy content of components with heat storage capacity (e.g., walls) will change now and then, even if the thermodynamic state of the system does not undergo a change. Results of such an exergy analysis are strongly under the influence of outdoor air temperature and cannot be compared from time to time, because each exergy has been calculated based on a different reference temperature at each time step.

In this work, the indoor air is defined as the reference state, because the heating/cooling systems inside the building are the focus, here. Based on this proposed approach, energy streams have zero exergy at indoor air temperature, and non-zero (and positive) exergies at any other temperature level, either colder or warmer than the room. In other words, as the exergy content of indoor air equals zero, the directions of all exergies crossing room boundaries are always towards the room, which makes the analysis much easier. In addition, as the exergy of outdoor air is always larger than the exergy of indoor air, no exergy loss can be defined for the system (Sayadi et al. 2016).

6.1.14 VBA-Tool "ProfileMaker2.x" – Predicting User Behaviour for the design and analysis of energy systems

Detailed user profiles for different energy demands in buildings are a key element for concurrent analysis of demand and supply. Especially when analysing low-temperature district heating systems, not only the characteristics of the supply system, but also the energy demand of the buildings, caused by the inhabitants and appliances, have an impact on the overall demand. In an early stage of planning or if measured data are not available, prediction of user behaviour using randomized profiles offers opportunities for the analysis or design of energy systems. For the analysis of energy systems using these profiles, it is significant to indicate how many residents are at home and how many of them are active at what time. Furthermore, it is important at what time and how long which kind of electricity is required. In addition, it must be known how much thermal energy for space heating and domestic hot water is demanded at what time. All aspects have to be taken into account simultaneously for the analysis of complex energy systems since they are influencing each other as well as the energy demand. In the literature, approaches are found mainly focusing on one or two aspects mentioned above.

Hence a VBA tool was developed which enables the creation of stochastic user profiles by considering all aspects simultaneously. The profiles comprise the electricity demand of different domestic appliances and lighting, tapped DHW and body heat taking the presence and activity of the inhabitants of a building into account. The profiles can e.g. be applied for simulation of the heating demand (space heating and DHW production) of single buildings or districts. For this simulation the profiles are read-in by thermal simulation program (such as TRNSYS (TRNSYS17 2014)) (Kallert 2018).

The profiles are on high resolution and are ready for use in almost any simulation environment. As part of future research, high-resolution profiles for electricity and heat taking into account behaviour of residents will become increasingly important to investigate aspects of sector coupling and demand-side management or assessing hybrid energy networks. An example of the application can be found in chapter 4.1.2.

6.2 Summary and overview of the collected methods, models and tools

As part of the subtask of Annex 64 on the assessment methodology of tools and calculation methods, 14 models and tools related to exergy assessment, including six models, five methods and six tools are identified and collected. Five of those can assess energy systems by using optimisation algorithms. As seen in Table 3.

The models and tools are listed in Table 4 to identify the applicable stages, design stage or operation stage. Seven models can be applied in the design stage and nine models and tools can be applied in the operation stage. In addition, the list shows the boundary of systems to study, in which seven of those can assess energy systems from the building scale to community scales. Especially, **REMM** and **BEX** cover all scale of boundary depending on the problems. Four models such as **DEH**, **ExEx**, **DyEx**, **DEA** can be applied in operation stage for systems in single building scale. Thus, these have an important role in assessing on-site energy control and decision-making towards achieving low exergy processes.

Table 5 shows the objective functions of the models and tools. All models and tools can evaluate not only single objective function but also more than two objectives. LowEx:CAT and REMM define and use their original objective functions. LowEx:CAT evaluates demand of space, future potential of energy suppliers in addition to efficiencies of energy and exergy, CO_2 emissions, and economic impacts. REMM was further utilized to improve the status of districts in an original net-zero target, namely, the target of a Net-Zero Exergy District (NZEXD). NZEXD is a district that produces the same amount of energy at the same grade and quality as used on an annual basis.

Table 3 Classification and type of the regarded models in Annex 64

Tool or model	Assessment			Optimisation
	Model	Method	Tool	
1 **OLEC**		X	X	
2 **LowEx:CAT**	X	X		
3 **GICOP-DHS**	X			yes
4 **MODEO**	X			yes
5 **REMM**	X		X	yes
6 **CARNOT**			X	yes
7 **BEX**	X			
8 **ULTDH**		X		
9 **DEH**		X		
10 **ExEx**		X		yes
11 **DyEx**			X	
12 **DEA**			X	
13 **RS4DEA**	X			
14 **SPM2.x**			X	

Table 4 Stage and scope to apply the models and tools

		Target Stage		Target Scope				
		Design	Operation	Building	Group of Bldg	Districts	City	Regions
1	**OLEC**	X				X		
2	**LowExCAT**	X			X	X		
3	**GICOP-DHS**	X	X		X	X		
4	**MODEO**	X			X	X		
5	**REMM**	X	X	X	X	X	X	X
6	**CARNOT**	X	X	X	X	X		
7	**BEX**		X	X	X	X	X	X
8	**ULTDH**		X			X		
9	**DEH**		X	X				
10	**ExEx**		X	X				
11	**DyEx**		X	X				
12	**DEA**		X	X				
13	**RS for DEA**	X	X	X				
14	**SPM 2.x**	X		X	X			

6.3 SWOT Analysis of the tools

A SWOT (Strength, Weakness, Opportunity, Threat) analysis is a method to identify the features of subjects and to develop awareness and understanding towards planning an effective strategy. SWOT analysis is widely used in the fields of business or industry but also effectively available for other situations (Swot 2018).

- Strength: advantages (internal factors) to achieve the goal.
- Weakness: disadvantages (internal factors), which prevent the achievement.
- Opportunity: external factors, which contribute to the achievement.
- Threat: external factors, which prevent the achievement.

In this chapter, SWOT analysis is applied to understand the modelling approaches for low-exergy community studies. After identifying the four features, the following discussion points are presented.

- How the strength can be used.
- How the weakness can be overcome.
- How we can use the opportunity.
- How we can remove, avoid the threat.

6.3.1 Strength

Available to apply/combine existing building performance simulations (BPS)

Models for energy supply systems (such as centralized energy systems, power generation and supply systems or district heating network systems) are developed through many researchers in the simulation community. Energy community is the concept to manage energy production at energy demand points, including cluster of buildings. Study boundaries of centralized energy systems as supply side and that of

Table 5 Objective function of the models and tools

		Objective Function						
		Exergy	Pri. Energy	Temp	LC Cost	Opex	Env. Impact	Other
1	**OLEC**		X	X	X			
2	**LowEx:CAT**					X	X	X
3	**GICOP-DHS**				X	X		
4	**MODEO**	X	X		X		X	
5	**REMM**	X	X				X	X
6	**CARNOT**	X	X	X				
7	**BEX**	X	X				X	
8	**ULTDH**	X	X			X		
9	**DEH**	X	X					
10	**ExEx**	X				X		
11	**DyEx**	X				X		
12	**DEA**	X						
13	**RS4DEA**	-	-	-	-	-	-	-
14	**SPM2.x**	X	X	X				

building energy system analysis as demand side are different in the research field of energy simulation. In addition, energy simulation for centralized energy systems carrying out from macro scale utilizes long time steps (daily or yearly) with a top down approach.

That for on-site energy systems or building simulation carrying out from micro scale (by components, by room, or by building, etc.) utilizes short time steps (hourly or daily) with a bottom up approach. Both approaches are basically separated and combined approach is not established yet. Thus, if a model approach is applied, there are two ways, applying energy system model for single building by expanding its system boundaries to the community scale, or developing an energy system model, which features the system boundaries of building cluster. The approach makes it possible to see the impact of local decisions to the whole energy systems. However, energy demand is given and is not modelled in detail because of the resolution of modelling the boundary. Thus, the method to combine two different approaches, from macro to micro, or from micro to macro, is required. Input data for **LowEx:CAT** are simulated by TRNSYS.

Model integration based on existing modelling platforms (Matlab, Modelica, etc.)

Some tools are based on the existing modelling platforms such as Matlab, Modelica, etc. The concept of component based libraries is suitable for developing models depending on the projects or problems.

- **CARNOT** (Conventional And Renewable eNergy systems Optimization Toolbox) is a MATLAB/Simulink based toolbox which allows for the simulation of heating systems via predefined components in a library. It is structured in block sets which helps visualizing the modelled system.
- **The Dynamic Exergy Analysis Tool** applies a set of reusable Modelica-based models to perform a

fully dynamic exergy analysis. The exergy analysis tool has been developed in the equation-based, object-oriented programing language Modelica. The reason behind using Modelica as the modelling language is that Modelica is a powerful language to dynamically model thermohydraulic systems. The existence of broad and established component libraries is a further advantage.
- The calculation model in **OLEC** is developed using Matlab.

Multi boundary, Multi stakeholders (developer, planner, owner, engineer, user)

- **REMM** was developed as an analytical model to assess the level of match between the supply and demand of exergy as a means of determining the avoidable CO_2 emissions impact in the energy system. The model considers the primary energy spending that can be avoided across multiple sub-systems in the energy system through better exergy matches at the building, building cluster, campus, district, and/or city level. In this respect, the model utilizes an energy systems perspective with the objective of improving exergy matches and reducing avoidable CO_2 emission impacts.
- **MODEO** serves as a tool for the optimal design of energy supply systems for building clusters and districts. MODEO addresses aspects of energy performance, environmental performance, economic performance, and exergy performance, through a multi-objective optimization approach. The optimization results are presented in the form of Pareto fronts, through which decision-makers can understand the options and limitations more clearly and ultimately make better and more informed decisions.

6.3.2 Weakness

Demand profile

Accessibility of demand profile is not an original constraint for energy community study but the energy demand profiles of all buildings within the target boundary are required. However, in most of the cases, in general, the demand profile data are limited excluding the case of single ownership for several buildings, such as university buildings in campus or regional development by a municipality. Moreover, the information of building performance for existing buildings are uncertain. These limitations should be recognized well when we utilize a simulation approach for energy community.

- **Profile Maker2.x** generates profiles (txt.-files) of the presence and activity of the inhabitants as well as electricity and DHW tapping profiles automatically. The profiles can be applied to multi-family homes or to a cluster building consisting of single-family homes. For the simulation of the heating demand (space heating and DHW production), the profiles are read-in by thermal simulation program (such as TRNSYS).
- **OLEC** includes an energy profile generator as a simple energy balance model that calculates the hourly heat demand. The outcome is validated with numbers of energy from practice. The tweak-factors concerning the user behaviour e.g. presence of occupants, set-point of indoor temperature are used to calibrate the results with practice.

Not direct coupling yet

As mentioned under "Strength", some tools are developed based on the existing modelling platforms. It is an advantage for connecting them and keeping flexibility of the model approach. However, many others are developed separately, thus in general, we need to choose and use them correctly depending on the system boundary and problems to solve. Exergy theory can be the key aspect in linking different models and tools into one process.

Not full-open yet

Most of the models and tools shown in this guidebook are developed under academic/scientific activities and are not fully open at present. Thus, the number of models which is provided as open-source or free downloadable software is currently few. This guidebook discloses the theories behind each model, thus, the readers can understand and develop their own models by referencing these models.

Uncertainties

Uncertainties are not a unique weakness especially for modelling approaches in low exergy communities, but it is important to keep in mind that a lot of uncertainties are obtained in the simulation results because of the system boundary or input data. In case of a community approach, competitors are energy suppliers and district heating networks. Moreover, the demand profile is not always the same. Thus, future trend of energy demand and market competitiveness should be considered. On the other hand, there are various macro models or long-term perspective models such as MARKAL, OSeMOSYS, etc. Thus, the decision making for any community should be done by considering both sides of analysis.

6.3.3 Opportunities

Zero Energy Building

Nowadays, the promotion of zero energy building (ZEB) is becoming more implemented, thus on-site energy generation and management are getting more common. In this context, the demand for energy community study will be raised. That is why building scale energy/exergy study tools will be utilized increasingly.

- The aim of **DEH** is to develop diverse heat supply method to the nZEBuildings in the remote area where it is uneconomical to connect to the district heating grid. At the same time, the aim is to increase flexibility of the whole energy system by integrating the electricity grid and district heating grid.
- The purpose of **CARNOT** is the simulation of heat supply systems of individual buildings. However, through its open structure and expandability, CARNOT is also suitable to model district heating systems. So far, cooling components are not implemented in CARNOT, but can easily be included using self-programmed components. Real and generic studies can be conducted with CARNOT, since it is possible to use real data in form of time series as well as simulated buildings within the model. Exergy calculation is not yet part of the library, but can be easily included in CARNOT.

Urban planning, district development

In new construction projects, there is a potential to establish new energy communities by aggregating different building types. In this case, by coupling with building simulation tools to calculate building energy demand (Energyplus, TRNSYS, IDA-ICE, etc.), the potential of energy communities can be studied. On the other hand, in case of existing building blocks, the impact of on-site energy management for existing neighbour buildings becomes increasingly important.

Mature on-site energy technology in the market

On-site energy technology, such as heat pumps (HP), combined heat and power systems (CHP) or solar energy technology like photovoltaic panels (PV) or solar thermal collectors), etc. are reaching market levels and it becomes easy for energy end users to apply these technologies for their buildings. This transition of technology accessibility with a more distributed structure allows the chance to manage energy at the energy demand side. Thus, technical studies and tools become essential for the integration of exergy principles for guiding the uptake of these technologies.

Data accessibility

The trend of Internet of Things (IoT) technology makes it possible to collect various points of energy and thermal data to evaluate and assess the energy/exergy performance of energy systems. The methods are still under discussion and many projects are ongoing to address the challenges. Exergy analysis by using data from IoT sensors make it possible to support appropriate decision making for low exergy controls in community systems. Moreover, by collecting energy information, the orchestration of on-site energy generations within the community boundary can be possible. Thus, modelling approach for local energy management are highly demanded. Dynamic Exergoeconomic Analysis using Monitored Data and Dynamic Exergy Analysis Tool for HVAC Systems are examples of tools with related aspects, including an ExergySensor.

Climate action at the local level

Urban energy systems are currently responsible for 365 EJ or about 64 % of the total global primary energy use at about 567 EJ (IEA 2016). Baseline scenarios predict that urban primary energy usage could reach 618 EJ by the year 2050. However, scenarios that seek to limit global warming to at most 2 °C by the end of the century indicate that this value may be at most 432 EJ with a maximum increase of 18 % and even lower in 1.5 °C scenarios (IEA 2017). The use of exergy principles promises to be an effective tool towards addressing the urban energy challenge that presents an opportunity for the field in a time when climate action is being led at the local level. The attainment of more optimized energy demand and supply structures based on exergy principles can enable increased opportunities for CO_2 mitigation. Among the tools, **LowEx:CAT** and **REMM** are aligned with the objective of CO_2 mitigation through exergy analysis.

6.3.4 Threat

Insufficient boundary of analysis

For an energy community that can be guided with exergy principles, the comparison and impact analysis for existing and new energy infrastructure is essential. Sometimes, a conflicting or inefficient situation can be caused if the external boundary of the energy supply chain is ignored. It is important that the external boundary is evaluated appropriately.

- **REMM** can study an energy systems perspective for analysing the linkage between better matches in the supply and demand of exergy, the avoidance of additional primary energy spending, and re-

ductions in avoidable CO_2 emission impacts.
- **OLEC** is a model for the energy transition to gain understanding of trade-offs in energy infrastructure based on the principle of local hybrid energy infrastructures for utilization of locally available sustainable, low-value energy sources and energy storage.

Regulations and guidelines

Modelling approaches and tools can provide evidence based, robust solutions for possible future directions for the energy system considering many uncertainties. The models and tools can also provide effective findings through many case studies, and these findings can support the development of regulations or guidelines to establish low exergy communities.

Multi objective functions in decision making

A variety of stakeholders with different criteria are involved in an energy community. Depending on the views of each stakeholder, the priority of objective functions will be changed. It means that if optimisation is applied, the problem is inevitably multi-objective.

- The method of **Exergetic and Exergoeconomic Analyses** is designed by combining two analysis models, exergy and economy.
- Energy models in **OLEC** also involve detailed financial models to arrange financing and evaluating financial risks for supply contractors for these heat grid solutions.

7 Conclusions

The building sector is causing large greenhouse gas (GHG) emissions due to the energy demand for heating and cooling. Commonly fossil fuel based systems using combustion processes are used to satisfy these demands. The reduction of the GHG emissions is regarded as one of the core challenges in fighting climate change and realizing the energy transition. Exploiting these potentials and synergies demands an overall analysis and holistic understanding of conversion processes within communities. Here the exergy concept is applied to achieve better overall energy system designs.

As part of the project, communities are defined as a larger group of buildings, such as block of buildings and very large systems, such as cities which are characterised by a wide range of energy demands for instance heating, cooling and electricity. To cover this demand different energy sources with different quality levels can be used; e.g. low-temperature heat from geothermal sources at a "low exergy" level or through roof-top photovoltaics as "high-exergy" electricity. The fluctuating supply from renewable electricity production (e.g. from wind and PV power) offers both chances and challenges for future community energy systems. The interaction between (matched) energy demand and available (fluctuating) energy sources at different quality levels (exergy factor), especially for covering the heating and cooling demand, has to be solved at a local level, within the community.

The main objective of the reported research activity is to demonstrate the advantages of exergy evaluation and the potential of low exergy thinking on a community level as an energy and cost efficient solution in achieving 100 % renewable and GHG emission-free energy systems. The intention is to reach these goals by providing and collecting suitable assessment methods (e.g. holistic balancing methods). Furthermore, recommendations, best-practice examples and background material for designers and decision makers in the fields of building, energy production/supply and politics are provided in the report. Central challenges in achieving the objectives are the identification of the most promising and efficient technical solutions for practical implementation and aspects of future network management and business models for distribution and operation. Regarded aspects of transition management and policy will ensure the feasibility of the practical implementation.

As a framework for the research work, the theoretical background for the application of the exergy concept to analyses of energy utilisation in communities has been reviewed and put into relation between exergy and other (sustainability) indicators. Based on the outcome of previous research projects, a planning approach for communities has been derived. Although there is no common agreement in the scientific community working with exergy analysis, it is proposed to use the thermodynamic definition of exergy as a separate indicator to get insight into how well we are using our resources. The aim of an exergy analysis and of LowEx communities is to minimize the exergy losses as much as possible and as much as reasonable. It was also shown that other criteria such as renewability, storability or costs can best be regarded separately in addition to the exergy values. This way the insight from exergy analysis is gained, while additional reasons for choosing one system over another are added. This means sometimes exergy losses can be admitted, as long as they are justified by other reasons.

Furthermore, several approaches are presented on how to use the exergy concept in different phases of the design process for sustainable energy communities and an easy to understand/to use 10 step planning approach is presented. The use of exergy principles in the various phases of the planning process is shown. In the early design and performing (simplified) exergy analyses are used for further improving the energy system. For the last phase of detailed design and optimization, different tools can be used, which are also assessed by the Annex experts group.

Next to the planning approach, the most promising and efficient supply technologies allowing a flexible supply of different demands with maximal share of low-valued local and renewable energy sources are identified and described in the report. The technological considerations include both demand- and supply-side aspects. Hence the requirements for efficient buildings and user behavior are discussed. Furthermore, decentralised and centralised supply solutions and storage technologies, which serve as interfaces for community supply, are compared. Subsequently different supply technologies (e.g. heat pumps or solar thermal collectors) are described. As part of the supply solutions the significance of the regarded supply options in the context of a demand-adapted community supply was discussed. Furthermore, approaches for the exergetic assessment of the respective system component were discussed.

Different case studies, from different scales (building, district and city) and different countries are presented as part of the report. The examples consider the heat and electricity domains in one system in a way that makes calculations, comparisons (between systems taken with similar assumptions) and interpretations more consistent and useful compared to the energy approach.

In order to deal with various challenges such as improving the system performances in terms of sustainability and efficiency, exergy analysis was used through different methods and tools, which are also described in this report. Exergy analysis allows identifying the components or sub-systems that have potential for improvement. The case studies presented cover several scales and the different solutions highlighted at one specific scale can be scaled-up and scaled-down to be replicated. Exergy analysis was showed to be useful at all stages of development of an energy system: from the design phase (e.g. CITYOPT, Austria) to the operating (e.g. RWTH Aachen, Germany) and the renovation phases (e.g. Prêt-à-Loger, Delft).

Until now the exergy approach is neither popular nor extensively used for several reasons. First of all, the concept of exergy is newer and more abstract than the concept of energy as it is related to a specific system with its intrinsic constraints, boundary conditions and reference temperature. Another noticeable limitation of the exergy approach is that in order to be able to compare results, one should take care to make calculations with similar system boundaries and reference temperatures. Any comparison of uneven systems could lead to misinterpretations and biased or wrong conclusions. Indeed, the input of exergy varies greatly for the chosen system boundaries of a project. The broader the system boundaries, the larger the analysis. Considering a restricted system allows focusing on specific solutions to improve the system efficiency. However, the improvement identified at a lower system may not imply better exergy efficiency if a larger system is considered. That is the reason why for instance in Case study RWTH Aachen, Germany, the optimisation algorithms investigated several system boundary conditions for different subsystems.
From the different case studies at different scales, the following statements can be drawn:

- Buildings destroy more input exergy than they lose and produce. About 84-93 % of exergy consumed by buildings is destroyed by irreversibilities.
- Exergy-based control is suitable to achieve efficient building operation. Using dynamic simulation models, the exergy analysis can be fully automatized and used for model-based control.
- The exergy analyses based on annual measurements show that ULTDH systems with local electric booster have higher exergy efficiency compared to existing DH systems.
- A low energy demand can be achieved by high buildings standard and low thermal losses among the network, wide energy share produced from renewables and good exergy efficiency, compared to traditional thermal systems.
- Old production systems can be significantly improved in terms of exergy input and exergy efficiency by replacing part of the heat production from fossil fuels by heat production from low-exergy sources.
- Lowering supply and/or return temperatures increases the exergy efficiency of DHN and consequently the whole system. However one has to keep in mind when decreasing the supply temperature in the network, the water flow should be carefully considered to avoid an increase of the pumping cost.
- The low-exergy approach allows identifying which component/configuration of the system to focus on, in order to implement/improve low-temperature DH networks and so to save fossil energy, having a lower overall exergy input and also reduced CO_2 emissions. By implementing ULTDH, distribution heat losses can be saved substantially.

As part of the work within Annex 64, the assessment methodology of tools and calculation methods have been assessed. In total, 14 models and tools related to exergy assessment, including six models, five methods and six tools are identified and collected. Five of those can assess energy systems by using optimisation algorithms.

The models and tools are presented to identify the applicable stages, design stage or operation stage. Seven models can be applied in the design stage and nine models and tools can be applied in the operation stage. In addition, the system boundary of the study is shown, in which seven of those can assess energy systems from the building scale to community scales. Especially, REMM and BEX cover all scale of boundary depending on the problems. Four models such as

DEH, ExEx, DyEx, DEA can be applied in operation stage for systems in single building scale. Thus, these have an important role in assessing on-site energy control and decision-making towards achieving low exergy processes.

The objective functions of the models and tools are presented as well. All models and tools can evaluate not only a single objective function but also more than two objectives. LowEx:CAT and REMM define and use their original objective functions. LowEx:CAT evaluates demand of space, future potential of energy suppliers in addition to efficiencies of energy and exergy, CO_2 emissions, and economic impacts. REMM was further utilised to improve the status of districts in an original net-zero target, namely, the target of a Net-Zero Exergy District (NZEXD). NZEXD is a district that produces the same amount of energy at the same grade and quality as used on an annual basis.

The exergy analysis has the potential to support strategic targets such as the reduction of energy spending and the increase of the share of renewable energy on a long-term horizon.

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Appendix B: Additional information on case studies

Case/system	Title	Short description	Contact
Kassel, Germany	Geo-solar low-temperature district heating for the new housing development "Zum Feldlager"	Low-temperature district heating, central ground source heat pump, solar thermal energy, renewable energies, low-energy buildings	Dietrich Schmidt (dietrich.schmidt@iee.fraunhofer.de) Fraunhofer IEE (Germany) and Janybek Orozaliev (orozaliev@uni-kassel.de), Isabelle Best (best@uni-kassel.de), University of Kassel (Germany)
Germany	Exergy-based control strategy for HVAC systems		Roozbeh Sangi (rsangi@eonerc.rwth-aachen.de) and Marc Baranski (mbaranski@eonerc.rwth-aachen.de), RWTH Aachen (Germany)
Mannheim, Germany	Evaluation of community heating systems based on exergy analysis. 11 buildings in Mannheim, Germany	Solar thermal. Geothermal. CHP plant. Economical analysis. Ecological analysis. Exergy analysis. Energy analysis. Building cluster.	Paul Michael Falk, Frank Dammel (dammel@ttd.tu-darmstadt.de), TU Darmstadt (Germany)
Germany	Exergy-based analysis of renewable multi-generation units for small scale low-temperature district heating supply	Thermal Simulation, Low Exergy Communities Low Temperature Supply Structures and District Heating	Anna Kallert (anna.kallert@iee.fraunhofer.de), Fraunhofer IEE (Germany)
Milano, Italy	Politecnico di Milano-ABC dept. – new district energy concept in Segrate	New development district, Low-T district heating High-T district cooling, Biomass cogeneration BIPVs	Paola Caputo (paola.caputo@polimi.it), Federica Zagarella (federica.zagarella@polimi.it), Politecnico di Milano (Italy) and Ivar Baldvinsson, Charlotte Marguerite (charlotte.marguerite@ait.ac.at) Austrian Institute of Technology (Austria)
Florence, Italy	The application of BEX to a portion of urban system in the city of Florence (Italy)	Exergy, Building Exergy Model, Urban scale, Energy use map	Marta Giulia Baldi (marta.baldi@unifi.it), University of Florence (Italy)
Halifax, Canada	The application of BEX to the city of Halifax (Nova Scotia)	Exergy, Building Exergy Model, Urban scale, Energy use map	Marta Giulia Baldi (marta.baldi@unifi.it), University of Florence (Italy)

Case/system	Title	Short description	Contact
Princeton, USA	Princeton University district heating and geothermal	Cogen, Campus	Paul Michael Falk (falk@ttd.tu-darmstadt.de), TU Darmstadt (Germany) and Charlotte Marguerite (Charlotte.marguerite@ait.ac.at), Austrian Institute of Technology (Austria)
Areas with NZE-Buildings	Heating buildings with direct electrical heating by storing heat in the thermal mass during off-peak hours using predictive control	NZEBuildings, direct electrical heating, excess renewable energy, off-peak electricity, predictive control	Maria Harrestrup, Xiaochen Yang (xiay@byg.dtu.dk), Svend Svendsen (ss@byg.dtu.dk) Technical University of Denmark (Denmark) and Klaus Lund Nielsen (klaus.lund.nielsen@danfoss.com), Danfoss A/S (Denmark)
Micro tank concept to be compared to a demo project of a direct electrical heated system with ultra-low-temperature district heating	New concept of electric supplementary heating based on micro tank for domestic hot water preparation with ultra-low-temperature district heating supply	Ultra-low-temperature district heating, electrical supplementary heating, micro tank	Marek Brand (marek.brand@danfoss.com), Danfoss A/S (Denmark) and Xiaochen Yang (xiay@byg.dtu.dk), Svend Svendsen (ss@byg.dtu.dk), Technical University of Denmark (Denmark)
Bjerringbro, Denmark	Using ground water for ultra-low temperature district heating (ULTDH) in Bjerringbro city during winter and cooling of Grundfos buildings during summer (Denmark)	Ground water source for heating and cooling Ultra-low temperature district heating Control method Heat pump	Xiaochen Yang (xiay@byg.dtu.dk) and Svend Svendsen (ss@byg.dtu.dk), Technical University of Denmark (Denmark)
UrbanCascade, Austria	Cascading solutions between different building types	Cascading, heat pump integration, city wide District heating network	Ralf-Roman Schmidt (Ralf-Roman.Schmidt@ait.ac.at), Markus Koefinger, Charlotte Marguerite (Charlotte.Marguerite@ait.ac.at), Austrian Institute of Technology (Austria) and Itaru Takahashi (itaru@keyaki.cc.u-tokai.ac.jp) Tokai University (Japan)

Case/system	Title	Short description	Contact
NextGeneration-Heat, Austria	Economical and environmental optimal design of SH and DHW for 4 DHN in Austria	Low temperature district heating, Domestic hot water preparation, dynamic simulations	Charlotte Marguerite (Charlotte.Marguerite@ait.ac.at), Ralf-Roman Schmidt (Ralf-Roman.Schmidt@ait.ac.at), Eshan Ahmadian, Austrian Institute of Technology (Austria)
Olec-project	Optimization of Low-temperature Cluster grids in Districts	Low temperature heating grid, multiple heating sources, business models, cluster grids, district development	Eric Willems (e.willems@huygen.net) Huygen Engineers & Consultants
Vienna, Austria	CITYOPT - Study case of Vienna waste heat based micro DHN	Micro DHN, LTDH, Multi-sources, Storages	Charlotte Marguerite (Charlotte.marguerite@ait.ac.at) Austrian Institute of Technology (Austria) and Itaru Takahashi (itaru@keyaki.cc.u-tokai.ac.jp) Tokai University (Japan)
Östra Sala backe, Sweden	Net-zero exergy district case study of Östra Sala backe	Low temperature DHN, district heating driven white goods, CHP, GSHP, renewable energy	Siir Kilkis (siir@kth.se), Royal Institute of Technology (KTH) (Sweden)
KTH Campus buildings, Sweden	REMM analysis of building clusters on the KTH campus and Albano district	Low temperature DHN, sea water heat pumps, ATES, PVT as a more rational use of solar energy,	Siir Kilkis (siir@kth.se), Royal Institute of Technology (KTH) (Sweden)
TU Delft Campus buildings, Netherlands	Exergy scenario mapping of the TU Delft campus buildings	Low temperature DHN, geothermal energy, CHP, ATES, renewable energy	Siir Kilkis (siir@kth.se), Royal Institute of Technology (KTH) (Sweden)
Energy Potential Mapping: the 3D exergy profile	Energy Potential Mapping: the 3D exergy profile		Michiel Fremouw (m.a.fremouw@tudelft.nl), Delft University of Technology (Netherlands)

Appendix C: Additional information on Tools and Models

Name of the tool / model / method	Short description	Contact
Optimization of Low-temperature Cluster	The tool and method was developed for the optimization of Low-temperature Cluster Grids in Districts	Eric Willems (e.willems@huygen.net), Adnan Dedeoglu, Peter Op't Veld Huygen Consulting Engineers (The Netherlands)
Low Exergy Cluster Analysis Tool	The tool and the evaluation method was developed for the analysis of different energy supply strategies based on low-temperature district heating (LTDH) technology	Anna Kallert (anna.kallert@iee.fraunhofer.de) Fraunhofer IEE (Germany)
Geographic Information-based Cost Optimal Planning of District Heating System	The model was developed for cost optimal district heating system design and operation	Ivar Baldvinsson and Charlotte Marguerite (charlotte.marguerite@ait.ac.at) Austrian Institute of Technology (Austria)
Multi-Objective District Energy Optimisation	The model was developed the optimal design of energy supply systems for building clusters and districts	Cong Wang (congwang@kth.se) and Ivo Martinac (im@kth.se) Royal Institute of Technology (KTH) (Sweden)
Rational Exergy Management Model	The model was developed as an analytical model to assess the level of match between the supply and demand of exergy as a means of determining the avoidable CO_2 emissions impact in the energy system	Siir Kilkis (siir.kilkis@tubitak.gov.tr) The Scientific and Technological Research Council of Turkey (TÜBITAK)
Conventional And Renewable eNergy systems Optimization Toolbox	Description of a MATLAB/Simulink based toolbox (simulation tool)	Paul Michael Falk and Frank Dammel TU Darmstadt, Institute for Technical Thermodynamics (Germany)
Bulding EXergy Model	The developed model applies the Second Law of Thermodynamic to a building focusing on the interactions with the environment at the borders of the system.	Marta Giulia Baldi (marta.baldi@unifi.it) University of Florence, Industrial Engineering Department, DIEF (Italy)
Ultra Low Temp District Heating	The approach was developed for the evaluation of ultra-low temperature district heating	Xiaochen Yang (xiay@byg.dtu.dk) and Svend Svendsen (ss@byg.dtu.dk) Technical University of Denmark (Denmark)

Name of the tool / model / method	Short description	Contact
District Electrical Heating	The method and simulation model was developed for evaluation of heating NZEBuildings (nearly zero energy buildings) with surplus off-peak electricity, where it has not been connected to the district heating grid	Xiaochen Yang (xiay@byg.dtu.dk), Svend Svendsen (ss@byg.dtu.dk) Technical University of Denmark (Denmark) and Klaus Lund Nielsen (klaus.lund.nielsen@danfoss.com), Danfoss A/S (Denmark).
Exergetic and Exergoeconomic Analyses	Description of the principles of exergoeconomic analysis based on sources that can be found in literature	Paul Michael Falk and Frank Dammel TU Darmstadt, Institute for Technical Thermodynamics (Germany).
Dynamic Exergoeconomic Analysis Using Monitored Data	The model was developed for Dynamic Exergoeconomic Analysis Using Monitored Data	Saeed Sayadi (s.sayadi@tu-berlin.de) Technische Universität Berlin, Institute for Energy Engineering (Germany)
Dynamic Exergy Analysis Tool	The concept of object-oriented programing has been applied to develop a tool for the dynamic exergy analysis of HVAC systems suitable for a wide range of components	Roozbeh Sangi (rsangi@eonerc.rwth-aachen.de) and Marc Baranski (mbaranski@eonerc.rwth-aachen.de) RWTH Aachen University, E.ON Energy Research Center, Institute for Energy Efficient Buildings and Indoor Climate (Germany)
Reference State for DEA	The investigation to this method are focussing on the choice of a reference state for exergy analysis	Saeed Sayadi (s.sayadi@tu-berlin.de) Technische Universität Berlin Institute for Energy Engineering (Germany)
Stochastic Profile Maker 2.x	VBA tool was developed which enables the creation of stochastic user profiles (DHW, body heat and electricity)	Anna Kallert (anna.kallert@iee.fraunhofer.de) Fraunhofer IEE (Germany)

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The IEA EBC Annex 64 – LowEx Communities was a three year international research project which aims to demonstrate the potentials of low exergy thinking on a community level as energy and cost efficient solutions to achieve 100 % renewable and GHG emission-free energy systems. Central challenges are the identification of promising and efficient technical solutions for practical implementation. Aspects of future network management and business models for distribution and operation are as well essential for successful implementation and have been covered in the working phase. Aspects of transition management and policy will ensure the feasibility.

The main objective of the annex is to demonstrate the potential of low exergy thinking on a community level as energy and cost efficient solutions. The intention is to reach these goals by providing and collecting suitable assessment methods (e.g. holistic balancing methods). Furthermore, guidelines, recommendations, best-practice examples and background material for designers and decision makers in the fields of building, energy production/supply and politics are provided.

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