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SIMULATION AND EXERGETIC ANALYSIS OF RENEWABLE MULTI-GENERATION UNITS FOR A BUILDING GROUP

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Abstract
The building sector is responsible for more than one third of end energy consumption .The larger part of energy used for heating is won from highly exergetic fuels (e.g. coal, gas and electricity). Since living spaces are usually heated up to around 20 °C, low exergetic fuels are sufficient. Economically viable energy sources with low exergy share already exist for this application.
Main target of the work carried out is to demonstrate advantages of exergy assessment for increased efficiency of community supply. For this reason different supply scenarios, based on fossil and renewable energy sources, are investigated. The different renewable energy supply units are regarded individually or in two or three-way combinations. In this study on one hand renewable and fossil-based supply are compared and on the other hand benefits by merging of 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 exergetic assessment method is applied. Additionally simplified aspects of operational management are regarded to compare the different supply solutions. The evaluation of the scenarios clearly shows that the combination of innovative supply strategies and exergetic assessment leads to an "holistic understanding" of the energy conversion chain and offers prospects for optimized community supply. Additional economic considerations and an analysis of emissions should be included in the evaluation.
This paper represents modeling, simulation and exergetic analysis of renewable multi-generation units to supply a building group.

Keywords: Energy System Modelling, Low Energy Buildings, Exergy Assessment

1. Introduction

The building sector is responsible for more than one third of the end energy consumption and therefore for a large amount of greenhouse gas emissions. To identify potential savings holistic analysis of energy flows is necessary. In particular the application of exergy principles is especially important, allowing the detection of different available energy-quality levels

and the identification of optimal contribution to an efficient community supply. From this, appropriate strategies and technologies with great potential for the use of low-valued energy sources (LowEx) and a high share of renewable energies for heating and cooling of community supply systems can be derived. As part of this paper the "LowEx approach" [6] is used to demonstrate the benefits and the potential of this method to increase the efficiency of community supply.

2. Exergy analysis

In accordance to thermodynamic laws, exergy is the maximum theoretical work obtainable from the interaction of a system (energy flow or a change of a system) with its environment, until a state of equilibrium is reached between them [1]. Thus exergetic assessment shows a strong dependence on the selected reference environment. In this paper the outdoor air temperature is chosen using [9]. Other options for the selection of the reference conditions could be found in [2],[7]. In contrast to energy, exergy can be destroyed. In this way the exergy content expresses the quality, respectively the ability of transformation, of an energy source or flow. This property can be used for detection and quantification of the improving potential of complex community supply systems [2],[3]. Depending on the initial research question and purpose of the analysis, different system boundary definition applied to exergy assessment are found in literature e.g. [5],[7]. For exergy analysis carried out in this study the methodology described in [3] is used and adapted for assessment of community energy systems. This method is also known as the "LowEx"-approach, a more detailed description can be found in [4],[6].
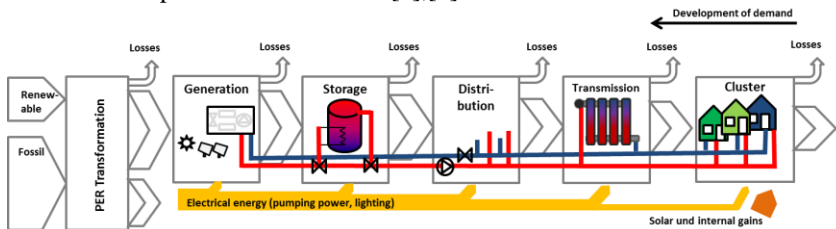

Fig. 1 Energy conversion chain used for modelling of a building group

For evaluating the exergy flows all transformation processes occurring at the community energy conversion chain needs to be taken into account (refer Fig. 1). The calculation of the energy and exergy demands starts at the demand side beginning at the building envelope. Supply chains are broken down into individual subsystems for the exergy analysis conducted in this paper. For each subsystem, the incoming and outgoing exergy flows are considered [3]. A description of other methods (e.g. advanced exergy analysis) could for example be found in [8].

3. Modelling of a small energy system

By using the simulation tool TRNSYS [10] a small energy system is modeled. According to Fig. 2 the model includes ten high energy standard residential buildings. To supply the building a local district heating (DH) network with substations, storages, and heat generation units: solar thermal collectors (ST), ground source heat pumps (HP) and gas-fired combined heat and power (CHP) are implemented. Additionally as a reference case a common decentralized supply technology using LNG boiler, without grid and without application of renewable energy sources (RES) is modeled. For both variants the ten buildings of the cluster are physically identical and are equipped with floor heating systems.
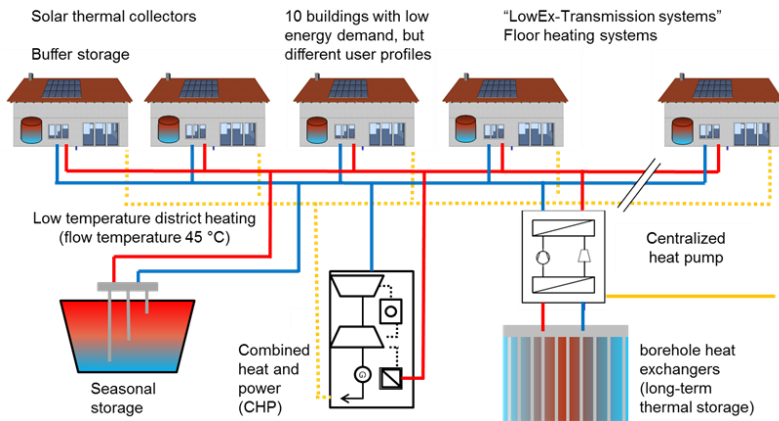

Fig. 2 Representation of heat supply combinations to a small district heating grid connected to a building group consisting of 10 residential buildings

To guarantee uninterrupted heat supply and to avoid undersupplying or oversupplying the emission systems, as well as the energy suppliers, are controlled by using weather forecasting. For modeling and simulation the weather data for Kassel (Germany) created by "Meteonorm" [9] is used.

Assumptions for buildings and thermal network

All buildings have a floor space area of 180 m² and are dimensioned for a specific heating demand of 45 kWh/m²a. This demand reflects an energy demand for new buildings according to EnEV 2009 [11].

Real settlements are characterized by variation of user behavior which results in greater deviation of each single building. For that reason the buildings are classified by different user profiles "average", "saver" and "waster" [12]. For each profile internal gains are varied in order to reflect a two-person household as well as a family of four at the same time.

"Average" and "saver" are equipped with night setback, which means that the room temperature is lowered by 3 °C for seven hours. In case of DHW preparation different stochastic DHW-tapping profiles were created using "DHWCalc" [13]. These profiles are classified corresponding to user profiles described above and differ in the temporal variance of tapping. The energy demand for DHW preparation is calculated using DIN V 18599 [14].

Table 1: User profiles for determination of the heat demand

	user type „average"	user type „saver"	user type "waster"
Room temperature	21 °C	19 °C	22 °C
Night setback	Yes	Yes	No
Air exchange rate	0,6 1/h	0,3 1/h	1,0 1/h

The DH network is designed as a radial network. To cover the heating demand and DHW demand simultaneously the design supply temperature is 45 °C. The thermal network is equipped by pre-insulated twin-pipes (U-Value = 0.027 (W/m²K)) with small diameters (DN50 and DN25) which leads to high efficient supply of the buildings. For coupling of the local low temperature DH network with the heating system the buildings are equipped with a substation (HAST). In the HAST the fluid coming from the district heating supply line is divided into two flows: heating fluid and DHW fluid. The fluid for space heating is provided directly to the building service systems. To provide the required temperature level for space heating a bypass is used for admixture of return line from the DH grid. For DHW preparation instantaneous heat exchangers are modeled taking Legionella prevention into account. In the event that the target temperature for DHW is not achieved, each building is equipped with an electric heating element.

Assumptions for the energie suppliers and storage facilities

The interconnection of energy suppliers and storage devices is shown in Fig. 3. The storages act as interface between the supply line of the DH-network and centralized energy supplying units. Two storage solutions are implemented; buffer and seasonal storage. Depending on the simulation scenario, both storages can be charged or re-charged respectively and activated or de-activated using the valves (1) and (2). If e.g. high solar yields are achieved, the seasonal storage is charged. As soon as the seasonal storage is recharged, HP and CHP can be activated to guarantee the uninterrupted heat supply. For the operation of the HP and CHP a small buffer memory is available. Depending on the selected supply scenario all supply units can be operated individually or in combination. All energy suppliers can be enabled or disabled, using the pumps and the valves (1)-(4). Additionally these pumps and the valves (1)-(4) regulate the mass flows. As long as the temperature level in the seasonal storage is above the return temperature of

the network (6) the residual heat can be used for reheating in the buffer storage, by activating valves (2) and (4). If the supply temperature is higher than the required supply temperature in the network the bypass valves (5) and (6) are used to control the return flow.
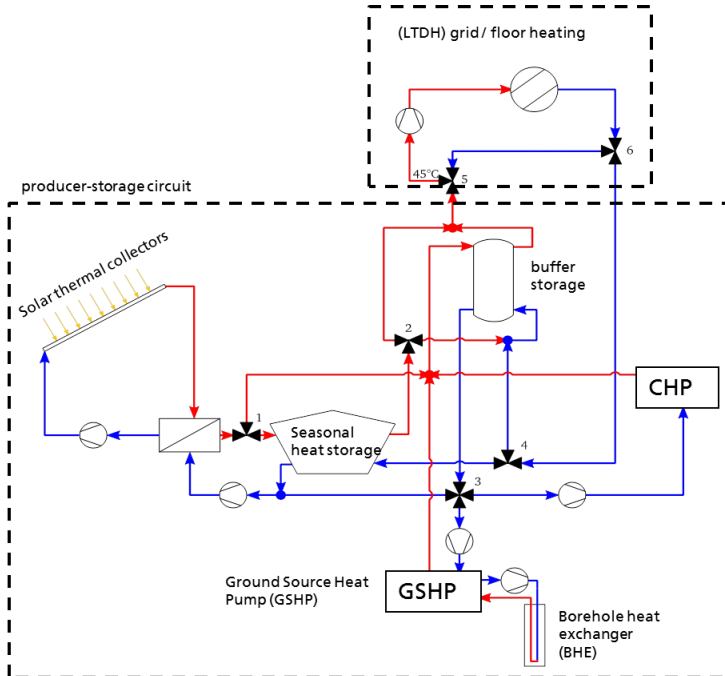

Fig. 3 Principle sketch of interconnection of energy suppliers and storage devices

4. Exergy-based analysis of case studies

For comparison and exergy analysis 7 renewable scenarios (centralized) and a fossil-based (decentralized) supply scenario are investigated. The selection of case studies using renewable energy sources is based on realized projects, where a high degree of innovation was targeted. The aim of this study on one hand is to compare renewable and fossil-based supply and on the other hand to identify benefits by merging several renewable energy suppliers for a small building group with high energy standard. In order to evaluate and assess the best supply solution by taking qualitative aspects into account, the exergetic assessment method is applied. Next to the exergy analysis simplified aspects of operational management are regarded as well. For analysis climate data (e.g. outside air temperature and radiation data) for Germany (City of Kassel) were used [9].

Representation of supply scenarios

The first 3 scenarios (scenario 1) deal with self-sufficient renewable supply variants. In scenario 2, two energy supplying units are interconnected. For supply scenario 3 three energy supplying units are interconnected. To compare renewable and fossil fuels as well as decentralized supply technologies in the context of exergetic evaluation a liquefied natural gas (LNG) boiler (scenario 0) is included in the evaluation.

Table 2: Representation of all investigated supply variants

	Scenario	Solar	Heat pump	CHP
0	LNG gas boiler	-	-	-
1.1	Solar Thermal	800 m² (100%)	-	-
1.2	Heat Pump	-	60 kW	-
1.3	CHP	-	-	60 kW
2.1	Solar Thermal + Heat Pump	200 m² (20 %)	60kW	-
2.2	Solar Thermal+ CHP	200 m² (20 %)	-	60 kW
2.3	Heat Pump + CHP	-	60 kW	5kW
3	Solar Thermal+ Heat Pump + CHP	350 m² (40%)	45 kW	20kW

Benchmarking parameters

Different benchmarking parameters can be found in literature suitable for energy and exergy assessment of energy conversion processes [3]. The most common benchmarking parameter for evaluating energy systems in general is the energy conversion efficiency η. This factor describes the ratio between the useful output of an energy conversion machine and the input, in energy terms. By using this parameter different occurring qualities or the ability of transformation [6] are not taken into account.

$$\eta = \frac{E_{use}}{E_{in}} \tag{1}$$

In order to assess occurring qualities the exergy efficiency ψ is used. In literature, different expression and definition of this parameter can be found [3]. In this work the so-called "overall exergy efficiency" is used [7]. The application of this exergy efficiency allows characterizing the total performance of a complete energy system. Overall exergy efficiencies of different energy systems (e.g. different supply scenarios for a building group) can be directly compared with each other, since the same reference temperature has been used for exergy analysis of all supply systems.

$$\psi = \frac{Ex_{use}}{Ex_{in}} = 1 - \frac{Ex_{loss} + Ex_{destroyed}}{Ex_{in}} \tag{2}$$

For allocating the CHP the "Carnot method" [16],[17] is used. Using this method the reference temperature is taken into account. Furthermore electrical and thermal efficiency are assessed independently [18].

5. Discussion of results

The comparison of energy efficiencies of the different scenarios is shown in Fig. 4. and leads to the conclusion that the LNG boiler is the favored solution. But in particular in new housing areas implementation of renewable energy sources (RES) in order to reduce CO_2 emissions is mostly targeted and there are often further restrictions (e.g. urban ventilation path). Taking this into account the HP or the CHP, or a combination of these units would be the favored. The solar thermal collectors show a low degree of efficiency in comparison and provide little incentive for implementation.
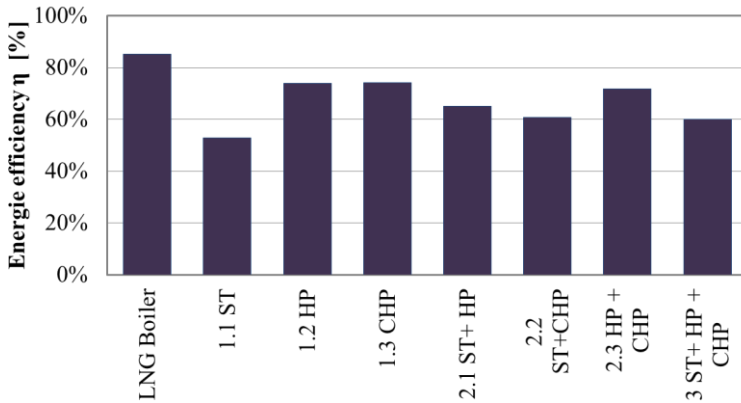

Fig. 4: Assessment of energy efficiency.

This picture changes significantly when taking exergy efficiency into account (Fig. 5). In particular the decentralized DH solution using RES shows advantages. In turn, the boiler solution is not a good option, since high exergetic fuels are burned and therefor the temperature level available to heat the room air is too high.

When comparing self-sufficient renewable energy suppliers solar heating is the most attractive heat source. However, there are large limitations: the heat is mostly generated during summer where the heat demand is low and must be stored with high heat losses until the heating season. Furthermore large-area solar collector-arrays need to be installed. This results in high costs that may not be economically viable. Additionally

the installation of large-area solar collector-arrays, especially in urban areas (densely populated areas), is often not feasible. Self-sufficient CHP or self-sufficient heat pumps offer another good supply option. Thus application of "Carnot Method" for allocating the CHP leads to high exergy efficiencies, although a combustion process occurs. In comparison to CHP the exergy efficiency of HP is lower, since the current German electricity mix [15] is used for heat supplying. In future energy system with an increased share of renewable energy this picture might change. A restriction on the use of HP is the space requirement if borehole heat exchangers are used.
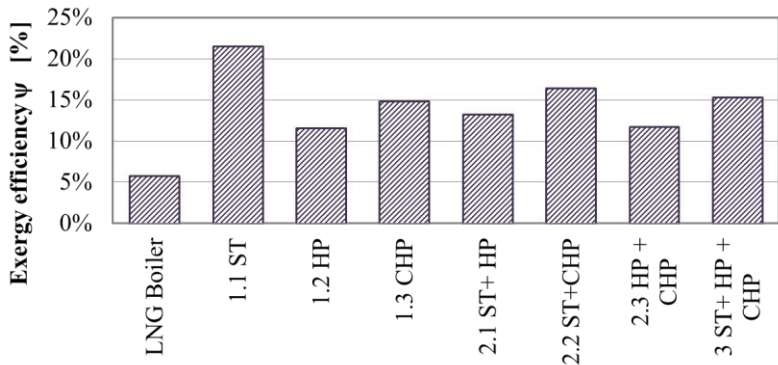

Fig. 5: Assessment of exergy efficiency.

In order to exploit the exergetic advantages of solar thermal energy and to identify benefits of multi-generation supply the CHP as well as the HP are combined with solar thermal collectors. From an exergy point of view, combination of CHP and ST is a very promising solution. But due to low operation time (< 3000h) [19] and expected high investment cost this supply variant is not a favorable option to supply such a small area. This would change, however, if the operational management would be optimized further. The combination of HP and ST shows significant potential for innovation since heat pump achieves an economic operating time (approx. 1700h) [20]. If the share of renewable energies in the electricity mix is increased or the HP is supplied by wind turbines or PV this scenario, in particular, offers very good options. Further energy analysis shows advantages of combining HP with CHP. This is refuted when taking exergetic considerations into account. A combination of HP and CHP for supplying the small building group may also be excluded for economic reasons, since the minimal required operating time is not achieved. A similar picture emerges for the combination of 3 supply units. Although the solar fraction is increased, the exergetic analysis shows, that combination of 3 generation units offers only small advantages for the supply of small building groups.

Conclusion and outlook

Main target of this paper is to demonstrate advantages of exergy assessment for community supply by taking qualitative aspects into account [3,7]. For this reason a homogenous building group consisting of ten residential low energy buildings is modeled. To supply the buildings a centralized and decentralized concept is implemented.

Different case studies based on fossil and renewable energy sources are investigated by using the model. The supplying units using renewable energy sources are regarded individually or in groups of two or three-way combinations. On one hand the case study aims to compare renewable and fossil-based supply. Furthermore benefits by merging of several renewable energy suppliers are identified. For evaluation and identification of the best supply solution, the exergetic assessment method is applied. Additionally simplified aspects of operational management (space requirement and operational time) are regarded to compare the different supply solutions.

In contrast to energy analysis exergy analysis facilitates the implementation of low temperature sources. It demonstrates that combustion processes (decentralized LNG boiler) reaching high supply temperatures should be avoided for supplying low energy buildings. In turn centralized supply based on DH using RES offers great potentials. The evaluation of self-sufficient, renewable-based supply solutions shows that advantages of solar thermal energy should be exploited by combining it with the energy suppliers CHP or HP. In particular a two-way combination of solar thermal with HP or CHP offers promising solutions. By taking simplified aspects of operational management and economics into account, the CHP shows disadvantages supplying such a small area. The combination of HP and ST shows limitation regarding the electricity [15] mix to supply the HP but also regarding space requirements. The advantages for using HP will increase if the share of RES increases in the electricity mix.

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.

Acknowledgment

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