An Exergy Evaluation on Micro-District Heating with Industrial Waste Heat in Vienna

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Abstract:

Exergy and energy are concepts that can be used to evaluate systems from different perspectives and can be applied to analyse systems performances. Although the exergy concept is not as extensively used as the energy concept, it allows highlighting specific aspects of systems. This paper describes an exergy analysis and compares the results to an energy analysis for a case study in Vienna which consists of a micro-district heating with industrial waste heat. This case study of Vienna is particularly interesting, since it brings a lot of knowledge and concepts for future developments of smart and micro district heating networks. Three scenarios are considered to evaluate different network configurations. The analysis leads to various non-trivial conclusions regarding the efficiency of using waste heat in a multi-sources micro district heating network.

Keywords:

Waste heat recovery, District heating, Thermal storage, Heat pump, Prosumer, Exergy.

1. Introduction

1.1. Background

Fourth generation district heating (4GDH) particularly requires control not only the quantity of heat but also the quality of heat being represented by low temperature levels. The CITYOPT project aimed at creating a generic platform for the assessment of urban energy systems as [1]. The case study of Vienna (Austria), a local micro district heating network (DHN), together with two other cases was used to validate this platform and evaluate its performances. A comparative energy analysis was carried out for the Vienna case study and energy performances, CO_2 emissions and costs were calculated of the system under various scenarios in previous works as [3] and [4]. The present paper brings together these two previous studies and compares the results with further analysis, namely exergy analysis.

This case study of Vienna addresses current and future challenges regarding DHN, such as how to integrate in a hydraulically connected system: renewable sources (heat pumps, solar collectors), industrial waste heat (fluctuating heat source, with different temperature levels), thermal storages (high and low-temperatures) in order to satisfy the heat demand of standard, low energy and prosumer buildings, with respect to environmental, energetic and economic objectives. Although its application would be limited within similar cases, this micro-DH can be used as an example that could be scaled up or adjusted to many cases of networks that has to be refurbished or extended. The final goal of using exergy is to help decision makers to make better choices for a better use of resources.

In [5], the main target of the work carried out is to demonstrate the advantages of exergy-based assessment for increased efficiency of small-scaled district heating supply schemes. Different supply scenarios, based on fossil and renewable energy sources, are investigated. The evaluation shows that the combination of innovative supply strategies and exergetic assessment leads to a more "holistic understanding" of the energy conversion chain and offers prospects for optimized low temperature district heating supply. However, the authors precise that economic considerations and an analysis of emissions are to be included in the evaluation to make the results of exergy assessment more meaningful.

Exergy is particularly adapted to 4GDH (low temperature technologies). As described in [6], exergy has been used already in a large number of studies on DH systems, in order to identifying inefficiencies and ways of improvement. Low-exergy systems and communities have been extensively studied and are presented in Annex 49 [7] and Annex 64 [2]. The LowEx approach is used in several international projects in order to promote the development of 4GDH and Low-temperature DHN.

In [8], it is presented that some theoretical points developed in the Annex TS1, which deals with the usage of low temperature district heating technology on a community level. To optimize the exergy efficiency of community supply systems the LowEx approach can be utilized, which entails matching the quality levels of energy supply and demand in order to optimize the utilization of high-value resources, such as combustible fuels, and minimizing energy losses and irreversible dissipation.

What can be conclude from this literature review is that the exergy concept is getting more popular within the scientific community, but it is not used extensively compared to the energy concept. This is due to a lack of explicit definition or interpretation of exergy. Most references of thermodynamics [9], explain that exergy shows “availability” of energy, “usefulness” of energy or maximum work extracted from an ideal heat engine. However, in most cases, those expressions are not suitable for thermal exergy flowing heating system but that for engine, because the output from heating system is not power but just heat. Heating potential itself should be explicitly expressed.

In the field of DH, exergy analyses are used in general for assessment of old networks (identifying heat losses inefficiencies, possibilities for improvement) and low-temperature DH networks (evaluation of new design and performances of networks). However, as the exergy calculations are not as straightforward as the energy calculations, the systems considered are mostly simple and do not involve multi-energy sources. The originality of this paper is to fill the gap of complex micro-dh networks (with multi-energy and multi-consumer types and multi-temperature levels requirements), by providing a comparison between energy and exergy analysis based on key indicators for decision making.

1.2. Purpose

Thermal exergy is a function of thermal energy, heat source temperature, environmental temperature (reference temperature) and thereby, both quantity and quality of heat can be articulated and be compared with exergy of the other various kinds of energy such as chemical, kinetic, electrical, solar and so on.

The purpose of this paper is to grasp the best solution for integrating micro-DH system with industrial waste heat from an exergetic aspect. In this paper, the study focuses on an industrial waste heat based micro-district heating, supplying energy efficient and standard buildings, equipped with renewables and fossil fuel heat sources, via thermal storages working at different temperatures and heat pumps.

This study case gathers several technical challenges around the main goal: how to optimally utilize the potential of waste heat? It is also a very interesting case because of its potential for replicability. Indeed, waste heat sources (from data centers, industrial processes, sewage, etc.) are widely distributed and available in every country, as well as mixed building stocks (buildings with various temperature requirements, energy efficient and standard buildings, etc.). Through in the study presented hereafter, the research questions concern the comparison between energy and exergy indicators applied to the case of a complex micro-DH network. Exergy results and economic results should be simultaneously discussed.

2. Methodology

2.1. Numerical simulation of the micro-DH system analysed

Figure 1 shows facilities of at the Austrian Institute of Technology (AIT). The Vienna case, also studied as [3], [4] and [10] is based on three office buildings located in the 21st district of Vienna, Austria: two energy efficient buildings, ENERGYbase (Eb) and FUTUREbase (Fb) and a standard building, TECHbase (Tb) of AIT. At the time of this study, Fb was under planning but not built yet, it was planned to be similar to Eb.

A nearby testing facility for train, Rail Tec Arsenal GmbH (RTA), rejects large amount of heat during its experiments. The heat is rejected from the chillers to the air via cooling towers, (3,394MWh were rejected in 2014), however, it has a high seasonal mismatch to the heat demand of the buildings and to recover it completely, a large scale storage would be required.

The thermal characteristics of the different buildings are summed up in Table 1. A gas boiler provides heat to Tb. Two ground source heat pumps and solar thermal panels provide heat to Eb. In this study, Fb is considered to have the same heat demand as Eb.

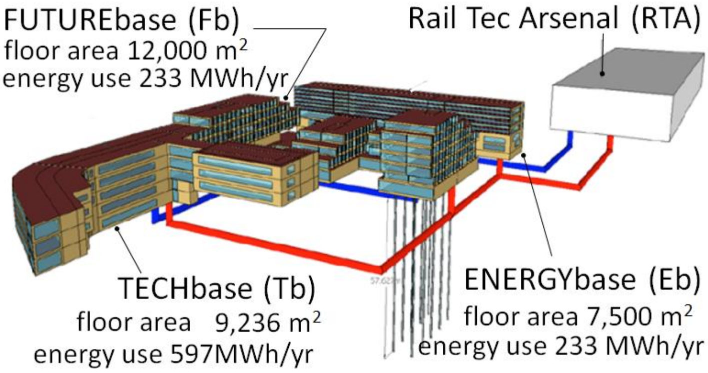


Fig. 1. AIT's facilities. They are three office buildings located in the 21st district of Vienna, Austria: two energy efficient buildings, ENERGYbase (Eb) and FUTUREbase (Fb) and a standard building, TECHbase (Tb). A testing facility in the nearby, Rail Tec Arsenal GmbH (RTA), rejects large amount of heat during its experiments.

Table 1. Thermal characteristics of AIT's facilities: own energy system, insulation level, supply temperature in heating and heating demand in the building.

	Fb	Eb	Tb
Own energy system	Heat pumps	Heat pumps & Solar thermal	Gas boilers
Insulation level	10.83 kWh/m^{2}yr	10.83 kWh/m^{2}yr	71.93 kWh/m^{2}yr
Supply temperature	35~45^{o}C	35~45^{o}C	60~80^{o}C
Heating demand	233 MWh/yr	233 MWh/yr	597 MWh/yr

The objective of building a micro-DHN in this area is to take advantage of the waste heat available to supply the three buildings considered to reduce their fossil fuels consumption as well as the CO$_2$ emissions associated. In addition to the waste heat source, the Eb and Tb buildings are "prosumers", which means that they can take the heat from the grid, but they can also feed the grid with the heat they produce by their own energy systems.

As the heat rejected by RTA is only dependent on the experiments taking place in the facility, it is not possible to forecast neither the amount of waste heat available nor its profile nor its temperature levels.

Two scenarios (1A, 1B) and one status quo scenario 1 are selected for the Vienna study case in the previous works as [3], [4] and [10]. They are described in Table 2 and illustrated by Figure 2. These scenarios are modelled and the operation of the whole system is simulated through APROS as [11], an energy modelling and simulation engine developed by VTT, Finland in order to determine the best design scenario for this micro DH system, based on three evaluation criteria: primary energy use,

CO_2 emissions, energy the operating costs and energy use. More details regarding the inputs, outputs and the method used can be found in [3], [4] and [10].

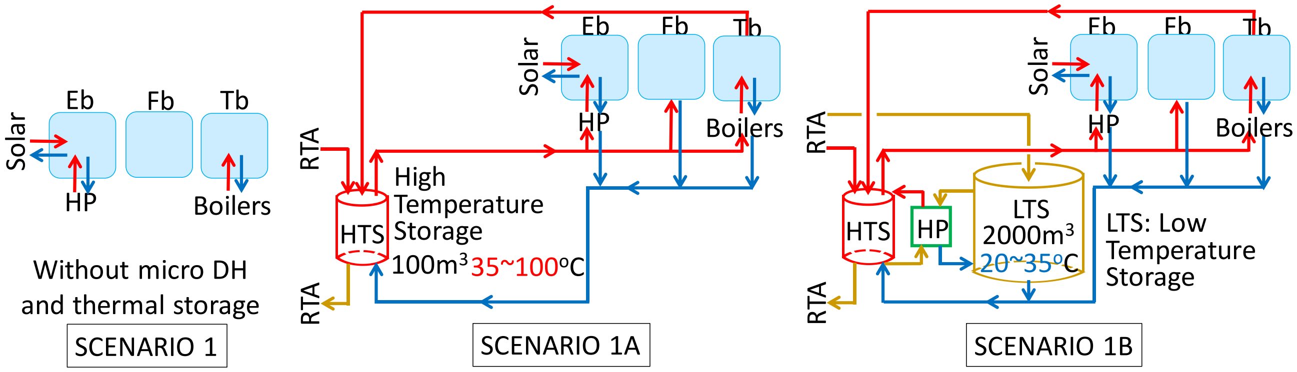


Fig. 2. Analysis scenarios in micro-district heating at AIT. Scenario 1 is the existing heating system without micro-DH and thermal storage. Scenario 1A is micro-DH system with high temperature storage (HTS) connected with RTA's waste heat. Scenario 1B is added low temperature storage (LTS) with scenario 1A. Red, orange, yellow and blue pipes represent temperature ranges of 60-80°C, 50-60°C, 20-35°C and 20-30°C respectively.

Table2. Description of the three scenarios in the analysis. Scenario 1 is exiting decentralized heating with a gas boiler and heat pumps. Scenario 1A is micro-DH system with high temperature storage connected with RTA's waste heat. Scenario 1B is adding low temperature storage with scenario 1A.

Scenario	RTA' waste heat	HTS	LTS	Booster HP
1	without	without	without	without
1A	with	with	without	without
1B	with	with	with	with

To deal with that characteristic of the waste heat source, two storages are included in the micro-DH (see scenario 1A and 1B on Figure 2). A water tank storage of 100 m^3 is used as a high temperature storage (HTS), for temperatures from 35°C to 100°C and another storage, made of nine borehole heat exchangers, is used as a low temperature storage (LTS) for temperatures from 20°C to 35°C, for a water equivalent capacity of 2000 m^3. A booster heat pump is coupled to the LTS to heat-up the outlet temperatures, to the required temperature level of the buildings. The control strategy of the storages is the following: waste heat goes to either to the HTS or to the LTS according to the temperatures rejected. If the HTS is fully loaded, the heat rejected from the RTA's facility at high temperatures, if any, goes also to the LTS. When both storages are full, the heat rejected from the RTA's facility cannot be recovered anymore and is released in the outside air.

2.2. Exergy analysis

An exergy analysis is carried out based on the numerical simulation results obtained from the energy analysis, such as water temperatures and energy flows. Exergy balance equations were derived against all the subsystems.

The exergy balance equations were set for the analysis based on references [12] and [13]. For instance, Equation (1) expresses the exergy balance of the heat pump in Energybase. Electrical exergy is supplied to the heat pump and because a of large exergy consumption, the small portion of remaining exergy is discharged from the heat pump which becomes the gross thermal exergy supply to Energybase.

In Vienna, the electricity is mainly generated by gas-fired and hydro power plants. Equation (2) and Equation (4) are exergy balances in the gas-fired power plant and the hydro power plant, respectively. Equation (3) and Equation (5) indicate primary input exergy for the gas-fired power plant and the hydro power plant, respectively. It is important to consider the exergy input for electricity supply to the heat pumps and booster heat pump of the system, as it is not a negligible proportion of the exergy input to the system. The shares and power generation efficiencies in power plants are assumed based on recent actual values as shown in Table 3.

$$x_{el} - s_{ghp}T_o = c_{pw}\rho_w V_{wEb}\left\{\left(T_{sEb} - T_{rEb}\right) - T_o \ln\frac{T_{sEb}}{T_{rEb}}\right\} + \left(1 - \frac{T_{othp}}{T_o}\right)q_{whp} \quad (1)$$

$$x_{hdr} - s_{ghdr}T_o = f_{hdrs}x_{el} \quad (2)$$

$$x_{hdr} = e_{hdr} = \frac{1}{f_{hdre}} f_{hdrs}x_{el} \quad (3)$$

$$x_{gas} - s_{ggas}T_o = f_{gass}x_{el} \quad (4)$$

$$x_{gas} = \gamma_f e_{gas} = \gamma_f \frac{1}{f_{gase}} f_{gass}x_{el} \quad (5)$$

Table 3. Assumption related to primary energy and exergy. Share of power source, factor of power generation, factor of exergy to energy in LNG and low heating value of LNG.

Share of power source [-]	Factor of power generation [-]	Factor of exergy to energy in LNG [-]	LHV of LNG [MJ/kg]
Hydro 0.55[14] Gas 0.45[14]	Hydro 0.80[14] Gas 0.46[14]	0.93[9]	54.5[9]

In this paper, the system under study is assumed to be composed of power plants supplying electric power to heat pumps, heat pumps, the gas boiler and three buildings. RTA's facility is outside the system boundary, though its waste heat is utilized by the micro DH system in scenario 1A and 1B. In this paper both waste heat and solar heat are regarded as primary input to the micro DH system studied. Supplying waste heat is not the original purpose of the RTA's facility, but it is rational to regard the RTA's facility as one of subsystems in the micro DH system. Therefore, RTA's waste heat was one of primary inputs for the micro DH system. All the exergy flows were calculated with reference to the outside air temperature at each time. The outside air temperature in dynamic is regarded as reference temperature for all the subsystems including heat pumps in this paper.

Exergy decrease in accordance with entropy generation is often expressed as "exergy destruction". However, the term, "destruction" enables us to imagine the process of breaking down from the whole to pieces and the total pieces are conserved. On the other hand, the term, "consumption" has the meaning being completely opposite to conservation. Therefore, the authors regard exergy consumption is much more suitable than exergy destruction and use this term in this paper.

3. Results and discussion

3.1. Exergy flows

Figure 3 illustrates the exergy flows (MWh/year) calculated with results of dynamic simulations of scenario 1. In this exergy flow diagram, the difference between the sum of the values on the left side of each component (e.g. gas boiler, 1175 MWh/year) and the sum of the values on the right side (e.g. gas boiler, 72 MWh/year) implies an exergy consumption within the subsystem considered (e.g. gas boiler, 1103 MWh/year).

The gross thermal exergy supply to the two low-energy buildings, Eb and Fb, is identical , while the gross thermal exergy supply to Tb is 4.6 times higher due to a lower insulation level.

In case of space cooling, the supply temperature of Eb or Fb is lower than the environmental temperature and the return temperature is higher than the environmental temperature, as a result, the thermal exergy can be removed from the building in gross value. Therefore, the gross thermal exergy removals indicated on Fig. 3 are 0.515 MWh/year.

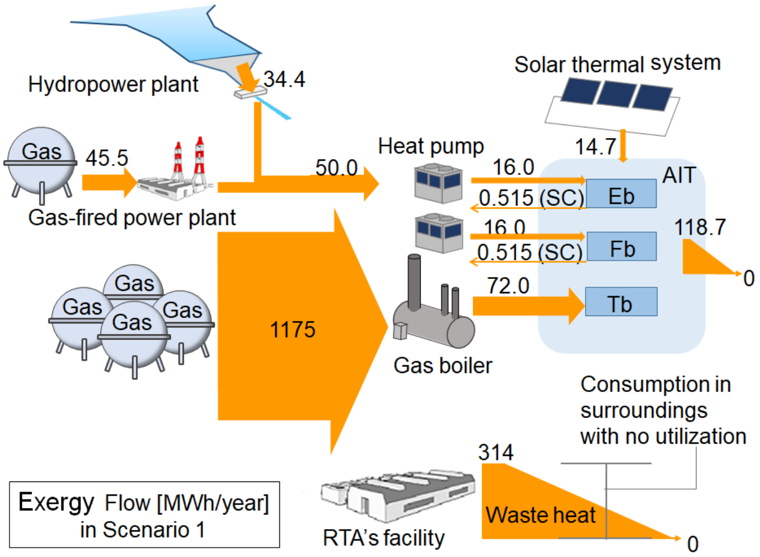


Fig. 3. Yearly exergy flow in scenario 1. Heating systems are decentralized: gas boiler, heat pumps in each building. SC indicates space cooling. The difference between the sum of the values on the left side of each component and the sum of that on the right side implies an exergy consumption within the subsystem considered.

The exergy input for the gas boiler is 1175 MWh/year and remarkably large. This is mainly caused by frequent turning on/off of the main boiler due to partial heating loads.

The amount of waste thermal exergy from the RTA's facility is 314 MWh/year, which is 2.7 times the thermal exergy supply from two heat pumps, the boiler and the solar thermal system. However, all of this abundant waste thermal exergy is not utilized in any heating purpose and all consumed in the outside air.

The total value of thermal exergy input for the buildings is 118.7 MWh/year and becomes zero through exergy consumption originated from heat dispersion inside and outside buildings.

Figure 4 shows the exergy flow in scenario 1A. In this scenario, a small portion of waste thermal exergy from the RTA's facility, 10.3 MWh/year is supplied into the HTS.

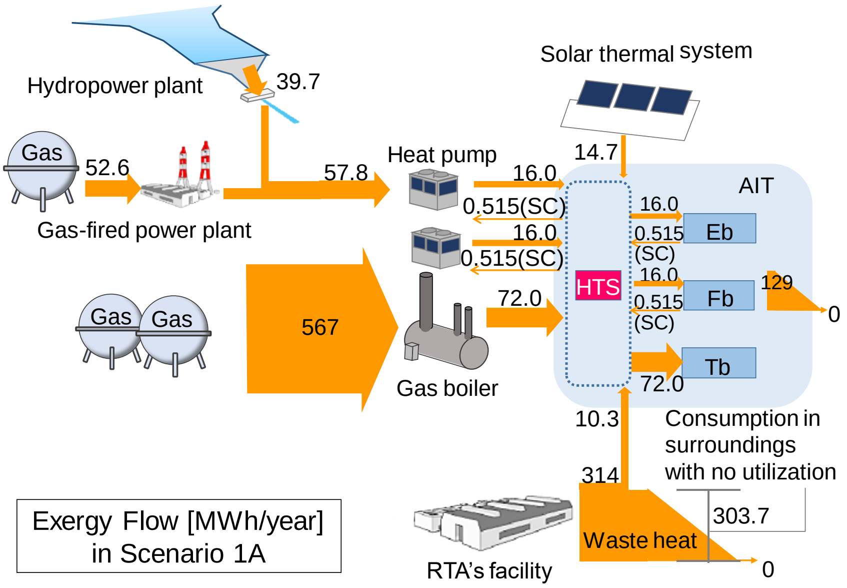


Fig. 4. Yearly exergy flow in scenario 1A. In this scenario, a small portion of waste thermal exergy from the RTA's facility, 10.3 MWh/year is supplied into the HTS.

The exergy input for the gas boiler is reduced in 52% compared to scenario 1. Because the use of the HTS makes the working time of the gas boiler shorter than scenario 1. The total gas exergy, including the primary input for heat pumps, is 49% less than in scenario 1. The total value of thermal exergy supplied to the buildings is 129 MWh/year (this equals the sum of =14.7+16.0 +16.0+72.0+10.3) and is all consumed inside and outside the buildings. The rest of waste thermal exergy from the RTA is all consumed in outside air without any utilization.

Figure 5 shows the exergy flow in scenario 1B. The difference from scenario 1 is the presence of both the HTS and the LTS with the booster heat pump. In this scenario, a large portion of waste thermal exergy from the RTA's facility, 223 MWh/year is supplied into the LTS of Tb.

The exergy input for the gas boiler is reduced in 85% compared to scenario 1. Like in scenario 1, this is due to the use of the LTS, with large amount of waste heat from the RTA's facility, which reduces the operation working time of the gas boiler. However, the use of the LTS requires running its coupled booster heat pump. The total gas exergy including primary inputs for heat pumps and the booster heat pump is 542.2 MWh/year and is 55% less than the scenario 1.

The total value of thermal exergy supplied to the buildings is 341.7 MWh/year (this equals the sum of =16.0+16.0+72.0+14.7+223) and finally all consumed inside and outside buildings. The rest of waste thermal exergy from the RTA, 91.0 MWh/year is all consumed outside air without utilization.

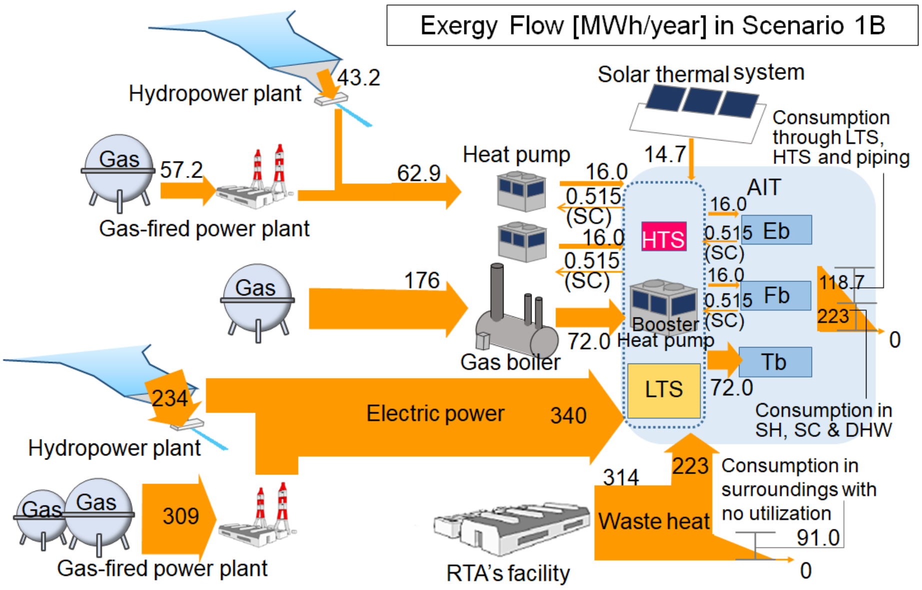


Fig. 5. Yearly exergy flow in Scenario 1B. The difference from scenario 1 is the presence of both the HTS and the LTS with the booster heat pump.

3.2. Exergy and energy efficiencies based on primary input

Table 3 shows Comparison between yearly efficiency between exergy and energy in the three scenarios. In this table, efficiency indicates the ratio of space heating demand divided its primary input. As already mentioned at the end of 2.2., waste heat and solar heat were included in primary input for the micro-DH system.

Yearly exergy efficiency based on primary input are 0.082 in scenario 1, 0.152 in scenario 1A and 0.098 in scenario 1B. On the other hand, yearly energy efficiency based on primary input are more than 0.6 among three scenarios. Especially, yearly energy efficiency of scenario 1A is beyond 1.0, because the share of heat supplied from heat pumps increase compared to scenario 1 instead of boiler's share down.

The increasing order of yearly exergy efficiency is 1<1B <1A and that of yearly energy efficiency is 1B<1<1A. There are differences in both increasing order and values of efficiency between yearly energy efficiency and yearly exergy efficiency based on primary input.

Table3. Comparison between primary and efficiency between exergy and energy. Efficiencies indicate the ratio of space heating demand divided its primary input.

Scenario	Primary exergy [MWh/year]	Primary energy [MWh/year]	Yearly exergy efficiency based on primary input [-]	Yearly energy efficiency based on primary input [-]
1	1270	1406	0.082	0.760
1A	684	946	0.152	1.130
1B	1057	1762	0.098	0.607

Figure 6 shows the monthly variations of exergy efficiencies based on primary input in the different scenarios. Exergy efficiencies in three scenarios are large in winter (between 10 and 30%) and small in summer (less than 10%). This is mainly caused by seasonal changes of primary exergy inputs and the thermal exergy demand is the same for all the three scenarios but the primary exergy inputs for each heat source differ depending on the heat sources involved.

In March and April, the exergy efficiencies in the scenario 1A are much higher than the other two scenarios because on the one hand by the small heat demand and the sufficient temperature level of the HTS in March. On the other hand, there is no booster heat pump and so no primary input to be considered from this side.

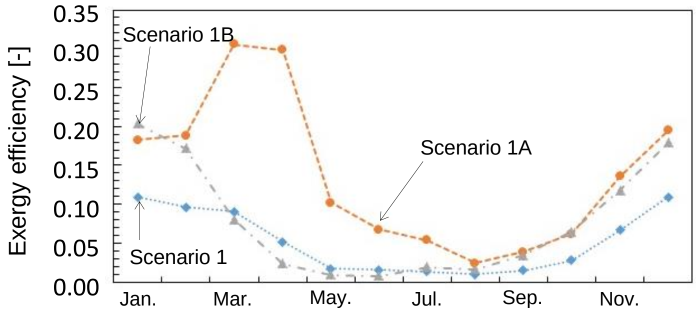


Fig. 6. Exergy efficiency in primary-input base. Exergy *efficiencies* were *obtained by dividing the total amount of gross thermal exergy supply by the total primary exergy input.*

All the exergy efficiencies are lower than 0.3. Especially in the scenario 1B, the exergy efficiencies are lower than the scenario 1A excluding January. Based on the energy concept, the scenario 1B appears to have the higher efficiency value, since this scenario has a higher heat pumps usage.

However as explained previously, the exergy analysis shows different results, the scenario 1A is the most efficient. This example illustrates the difference between the two analyses. The main benefit of the exergetic view is that it brings into the analysis an additional level of precision which allows finding the imperfection of the energetic view.

3.3. Dynamic change in primary exergy input

Here, we focus on dynamic change in primary exergy and energy input during several days in January and March. The exergy efficiencies in scenario 1A are much larger than the other two scenarios from March to May as shown in Fig. 6. There are small differences in exergy efficiencies between 1A and 1B from August to February. Focusing on the dynamic changes in primary exergy and energy input in January and March must clearly indicate the reason for the difference in exergy efficiency between these two months.

Figure 7 shows primary exergy input for the micro DH system during seven days in January in scenario1. The amount of solar thermal exergy is not visible on this diagram, because the amount of collected solar thermal exergy is quite small compared to the other exergies available due to the small solar collector area (285 m^2) and a much smaller ratio of exergy to energy in heat than in fossil fuel.

Figure 8 shows primary exergy input for the micro DH system during seven days in January in scenario1A. Here, the high temperature thermal storage reduces the operation time of the gas boiler compared to scenario 1, which also reduces the exergy input for the gas boiler from 100 to 400 kW. From the 1st to the 5th of January, both the hydropower exergy and gas exergy (via CHP) being primary inputs for heat pumps (through the electricity supply) are used more frequently than the scenario 1.

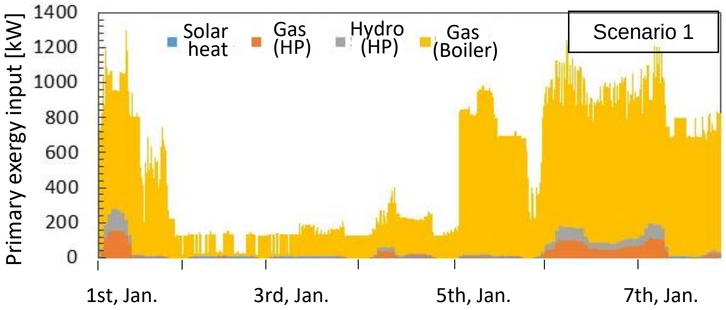


Fig. 7. Dynamic change of primary exergy input in scenario 1 (decentralized heating in each building) in January.

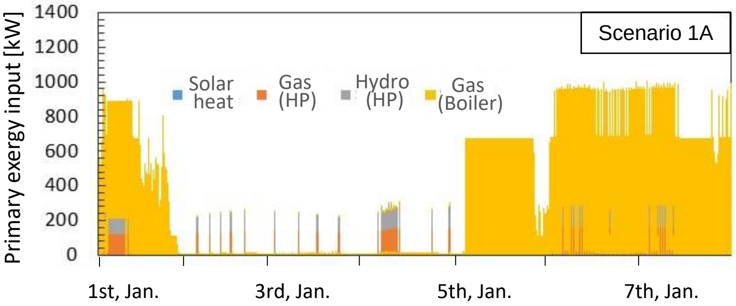


Fig. 8. Dynamic change of primary exergy input in scenario 1A in January. The high temperature thermal storage reduces the operation time of the gas boiler compared to scenario 1.

Figure 9 and figure 10 show primary exergy input for the micro DH system during seven days in March in scenario1A and 1B, respectively. In March the thermal exergy demand is smaller than in January. In the scenario 1B, the exergy input for the gas boiler is mostly eliminated excluding the from 19th to the 22nd of March. Instead of the gas boiler, the booster heat pump continuously requires (for its electricity supply) gas exergy from 40 to 200 kW and hydropower exergy from 30 to 180 kW as primary input.

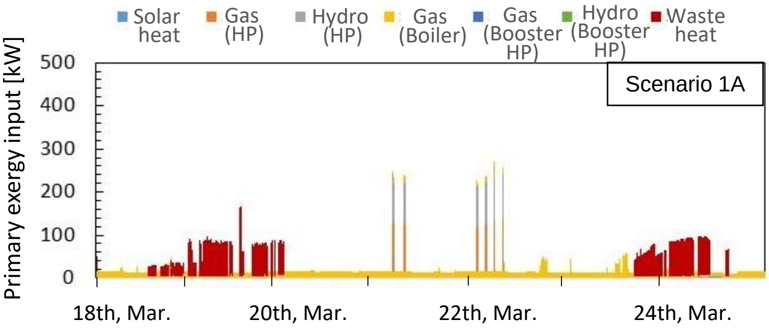


Fig. 9. Dynamic change of primary exergy input in scenario 1A in March. Gas exergy is much reduced in comparison with Figure 8, because heating demand in March is smaller than January.

The exergy input for the boiler is always less than 40 kW in both the scenario 1A and 1B in March. Indeed the inputs of waste thermal exergy and HTS in the scenario 1A decrease the boiler's output. Beside these, waste thermal exergy 20 to 180 kW is fed into the LTS on the 18th, 19th, 20th, 23rd and 24th of March.

Among three scenarios, the micro DH is operated with the smallest primary exergy input in the scenario 1A, because the exergy input for the boiler is partially replaced by the HTS and input of waste thermal exergy. The temperature level of the LTS is not high enough to supply heat to the network without the booster heat pump working, but the HTS contains heat at a sufficient temperature level to supply the network together with the heat pumps working shortly, in March.

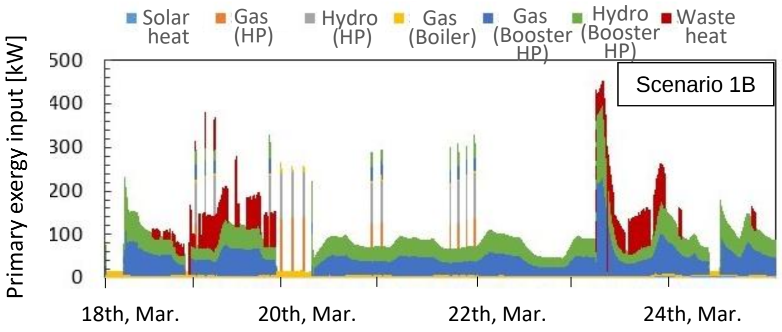
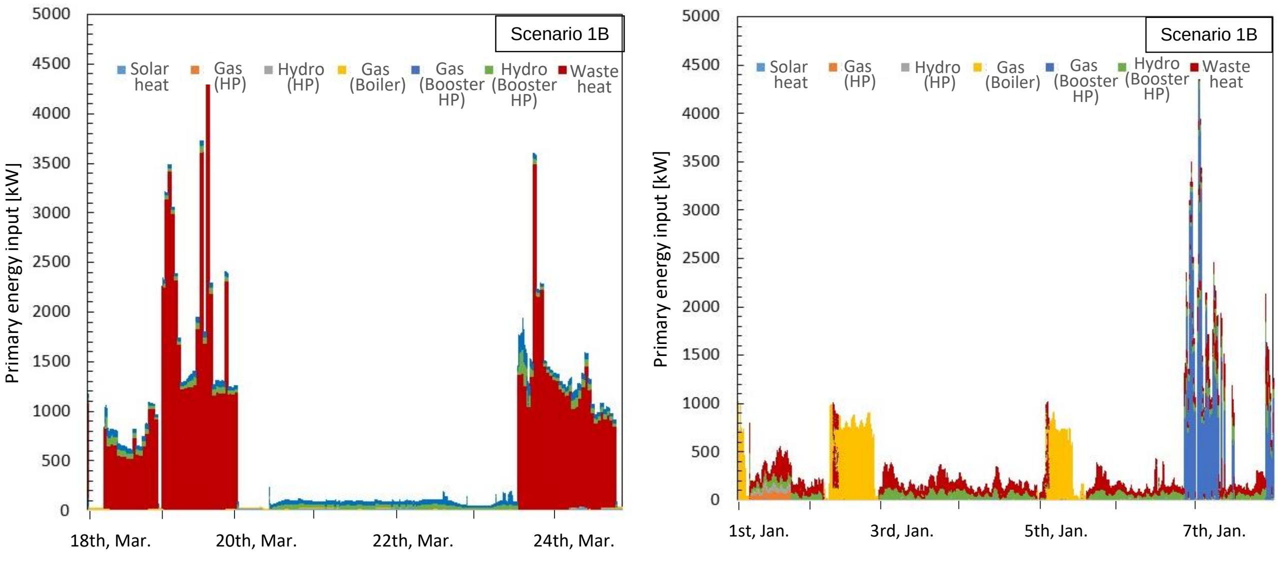


Fig. 10. Dynamic change of primary exergy input in scenario 1B in March. Instead of the gas boiler, the booster heat pump continuously requires gas exergy from 40 to 200 kW and hydropower exergy from 30 to 180 kW as primary input.

Figure 11 shows primary energy input for the micro DH system during seven days in March and January in scenario 1B. On one hand, the amount of waste thermal energy injected into the LTS is equivalent to ten times to twenty one times thermal energy use in buildings. On the other hand, in January, the amount of waste thermal energy injected into the LTS is smaller than 300 kW and hydro and gas energy for supplying electric power to the booster heat pump suddenly increase on the 7th in order to heat-up the LTS. Irregular change of industrial waste heat including shortage and working of the booster heat pump, thereby, make exergy efficiency of scenario 1B lower than scenario 1A.



(a)March *(b) January*

Fig. 11. Primary energy input in scenario 1B in March and January.

4. Conclusion

This paper describes results of an exergy analysis on micro-district heating with industrial waste heat in Vienna. Findings are the following.

Primary exergy input of LNG is reduced in 49.2% against decentralized heating (scenario 1) by means of high temperature storage (100 m^3, over 45^{o}C, scenario 1A). Adding low temperature storage (2000 m^3, 25~35^{o}C, scenario 1B) reduces primary exergy of LNG in 65.6% against Scenario 1.

The increasing order of yearly exergy efficiency is 1<1B <1A and that of yearly energy efficiency is 1B<1<1A. There are differences in both increasing order and values of efficiency between yearly energy efficiency and yearly exergy efficiency based on primary input.

Exergy efficiency in primary input base in Scenario 1A is 0.07 ~ 0.32 from March to July and the largest among the three scenarios. In the three scenarios, all the exergy efficiencies are lower than 0.3.

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 imply a better efficiency.

It is necessary to ensure industrial waste heat with both a sufficient quantity and a sufficient temperature level and to store without a booster heat pump in the micro-district heating system, in order to realize high exergy efficiency and large primary input reduction.

The comparison between energy and exergy indicators highlight the need for further discussions on the necessary other criteria for decision making.

Nomenclature

Example:

c_p	constant pressure specific heat, J/(kg K)
V	volume flow rate, m^3/s
T	temperature, [K]
q	thermal energy flow, W
s_g	entropy generation rate, W/K
x	exergy flow, W
e	energy flow, W
f	power generation efficiency of power plant

Greek symbols

ρ	density
γ	factor of exergy to energy in gas (LNG)

Subscripts and superscripts

w	water
Eb	Energybase [m^3/s]
sEb	supply for Energybase (at the inlet of the substation)
rEb	return for Energybase (at the outlet of the substation)
o	the outside air (environment)
$othp$	the outlet of the heat pump in Energybase
whp	waste heat from the heat pump
ghp	entropy generation of the heat pump originated from heat generation
f	liquid fuel ([9])
el	electricity
hdr	hydro power
$hdre$	power generation efficiency of the hydropower plant
$hdrs$	share of hydropower in Austrian power generation
gas	gas thrown into the gas-fired power plant

gase	power generation efficiency of the gas-fired power plant
gass	share of the gas-fired power in Austrian power generation

References

[1] CITYOPT FP7 project – Available at: <http://www. cityopt.eu/> [accessed: 10.2.2020]

[2] Annex 64 – Available at: <https://www.iea-ebc.org/projects/project?AnnexID=64/> [accessed: 10.2.2020]

[3] Marguerite C., Schmidt R.R., Pardo-Garcia N. and Abdurafikov R., Simulation Based Multi-Criteria Evaluation of Design Scenarios for an Industrial Waste Heat Based Micro District Heating Network Supplying Standard and Low-Energy Buildings, Proceedings of The 15th International Symposium on District Heating and Cooling, September 4th to September 7th, 2016, Seoul, Korea. Energy Procedia, vol. 116, pp. 128–137, 2017.

[4] Marguerite C., Schmidt R.R., Pardo-Garcia N., “Concept development of an industrial waste heat based micro DH network”, Proceedings of CISBAT 2015; p. 597-602, 2015.

[5] Torío H., Schmidt D., Development of system concepts for improving the performance of a waste heat district heating network with exergy analysis, Energy and Buildings, Vol. 42, Issue 10 , pp. 1601-1609, October 2010.

[6] Baldvinsson I., Nakata T., A comparative exergy and exergoeconomic analysis of a residential heat supply system paradigm of Japan and local source based district heating system using SPECO (specific exergy cost) method. Energy, vol. 74, pp. 537-554, 2014.

[7] Kallert A., Schmidt, D. Bläse T., Exergy-based analysis of renewable multi-generation units for small scale low temperature district heating supply. The 15th International Symposium on District Heating and Cooling, 04-07 September 2016, Seoul, South Korea. Energy Procedia, vol. 116, pp. 13-25, 2017.

[7] ECBCS Annex 49. Low Exergy Systems for High-Performance Buildings and Communities. Summary report – Available at: <http://www.iea-ebc.org/Data/publications/EBC_PSR_Annex49.pdf.> [accessed: 19.5.2020]

[8] Schmidt D., Kallert A., Blesl M., Svendsend S., Nord H. Li, N., Sipila K.. Low Temperature District Heating for Future Energy Systems. The 15th International Symposium on District Heating and Cooling, 04-07 September 2016, Seoul, South Korea. Energy Procedia, vol. 116, pp. 26–38, 2017.

[9] Dincer I. and Rosen M., EXERGY: Energy, Environment and Sustainable Development, Elsevier Science, p. 111-222, 2007.

[10] Pardo N., Nadler F., Marguerite C., Kelly B., “CITYOPT – Holistic Simulation and Optimisation of Energy in Smart Cities – Vienna Study Case”, Proceedings of ICERE 2015.

[11] APROS software – Available at: <http://www.apros.fi/en/> [accessed: 10.2.2020]

[12] Shukuya M., Exergy -- Theory and Application in the Built Environment, Springer-Verlag London, p. 111-222, 2013.

[13] Takahashi I. and Nemoto S., The influence of piping thermal insulation on indoor climate and exergy consumption related to hot water floor heating in Tokyo, Energy Procedia 2015, 78, p. 2632-2638.

[14] International Energy Agency, Energy Efficiency Indicators for Public Electricity Production from Fossil Fuels, IEA Information paper, 2008.