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Simulation based evaluation of large scale waste heat utilization in urban district heating networks: Optimized integration and operation of a seasonal storage

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ABSTRACT

The integration of renewable heat sources and industrial waste heat in urban district heating (DH) networks is essential for a sustainable and low-carbon heat supply and therefore a key element for a future prove energy system. Achieving this integration requires the investigation of different technical and infrastructural options, as well as economic analyses for improved implementation. In the city of Linz (Austria), the existing industry exhibits significant unused waste heat potentials which could be integrated into the existing urban DH system, however, a seasonal storage is required due to the competition with an existing waste incineration plant.

This paper shows, that a strategic operation of the seasonal storage could increase the number of charging cycles and thereby increase significantly the revenues of the system. This is mainly due to the combined utilization of the storage in a seasonal approach to shift the waste heat from summer to the winter period and as a short term buffer. Thus, the profits from actively participating on the electricity market with the existing combined heat and power (CHP) plants are increased.

1. Introduction

Currently, more than 2.000 district heating (DH) networks are operating in Austria. Besides some larger networks in urban areas (e.g. Vienna, Graz, Linz, Salzburg, Klagenfurt) the majority are small biomass bases rural DH networks, mainly created in the 1990s-2000s. The following data are extracted from Ref. [1] [1]. By 2016, the total share of DH on the low temperature heating marked in Austria is 25%. About 51% of the supply to Austrian DH networks is based on fossil fuels, the remaining share is distributed between waste incineration, biofuels and others. Waste heat from industry is below 2% of the total supply. However, within the new climate and energy strategy of the Austrian government [2], the importance of industrial waste heat from industries is mentioned several times.

In the province "Upper Austria", particularly in the city of Linz, significant waste heat potentials are available which could be used reducing the primary energy demand and the CO2 emissions of the DH system [3], [4], [5]. For achieving high shares of the waste heat, a large scale storage, i.e. a seasonal storage plays a key role to address the supply/demand mismatch and the supply competition with a waste incineration plant in summer times – see section 2.1.

This publication describes the simulation and evaluation of different scenarios for the waste heat integration in the Linz DH network, focusing on a seasonal storage in combination with different operational strategies, decreased network temperatures, network topology modifications and heat pumps.

Although seasonal storages have already been demonstrated mainly in rural DH networks focusing on solar integration (see section 2.2), the integration of waste heat in urban network using seasonal storage has not yet been considered in an Austrian framework neither internationally.

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[1] Due to different statistical approached and data used, other values can be found in the literature, e.g. Refs. [73,74].

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Abbreviations

CHP	combined heat and power
COP	coefficient of performance
DH	district heating
FGC	flue gas condensation
HOB	heat-only boiler
HP	heat pump;
HT	high temperatures
IWH	industrial waste heat
LT	low temperatures
MILP	mixed integer linear programming
O&M	operation and maintenance
RT	return temperature
ST	supply temperature
WI	Waste incineration

2. State-of-the-art review

2.1. Seasonal mismatch as main challenge for suppling waste heat into district heating networks

The utilization of waste heat from industries (e.g. steel plants) and the service sector (e.g. data centers) is well known practice and state-of-the-art. However, there are currently significant potentials of waste heat still unused, e.g. Refs. [6], [7]. In Ref. [8] it is estimated, that about 4% of the heating and cooling demand in the residential and service sector could be covered by waste heat, but only 0.2% is actually used in DH networks.

An important barrier for integrating significant shares of waste heat in DH networks is the seasonal mismatch between the demand and the supply profiles as well as the competition with other renewable or low carbon energy sources in summer times, including solar- and geothermal energy as well as ambient heat via heat pumps (e.g. Ref. [9]), see also Fig. 1, left. From the DH network operator's point of view, the waste heat must be cheaper than the marginal production costs of the existing supply units e.g. Refs. [10], [11], creating a merit order of all heat supply, see Fig. 1, right. The marginal production costs of relevant supply units can be summarized as follows:

- Supply units that consume fuels for heat only production, e.g. fossil fired or biomass boilers are having high marginal costs.
- Combined heat and power (CHP) plants in general have medium to low marginal costs, depending on the ratio between fuel and electricity costs. They can be negative if the revenues from selling electricity exceed the fuel and other operation costs. However, this is highly depending on the energy markets, having a volatile nature.
- Heat pumps can have very low marginal costs, if the seasonal performance factor is high and/or very low electricity prices apply.
- Solar- and geothermal energy have (almost) zero marginal costs due to (almost) zero operational costs – however, for solar energy the full availability is obviously limited to summer times.
- Waste incineration plants have often very low or negative marginal costs due to revenues from electricity sales (if applicable) and negative fuel costs caused by the revenues for providing municipal waste disposal services. Additionally, a "must-run" condition applies due to limited storage stability of the waste [12], making them an essential base load provider in DH networks.

However, those costs are highly depending on national and international regulations, subsidies, taxes, energy markets and technical characteristics of the supply units (i.e. efficiency), e.g. Ref. [13]. The marginal costs of waste heat mainly depend on the chosen business model and the contract between the heat supply company and the company that emits the waste heat. If heat pumps are used, also electricity costs apply (see above). If the waste heat utilization is considered as "cooling as a service" from the DH network operator, the marginal costs of waste heat can be negative or zero (a business model applied in Ref. [14]). However, this requires all investments (heat extraction, collection, processing (i.e. using a heat pump for temperature adaptation) and transport) to be done at the network operator side. Since cooling as a service is a rather new business model, positive marginal costs for waste heat utilization usually apply.

The merit order, which is based on this marginal costs structure represents the priorities for plant scheduling. In summer times, only the units with the lowest marginal costs will be operated until the heat demand is covered. Every additional supply needs to be either interrupted or cooled down to the ambient if an interruption is not possible (e.g. for solar energy). As a consequence, the full load hours of those units are reduced and the payback time is significantly shortened, especially for units with high specific investment costs (such as geothermal energy, waste incineration and solar energy).

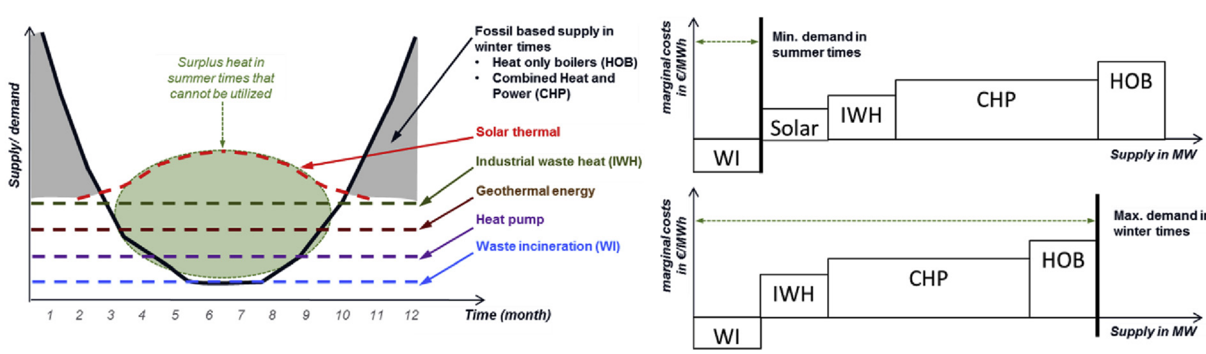

Fig. 1. Left: schematic example of the competition between different heat supply units in summer times, right: merit order of heat supply units in summer (top) and winter (bottom), schematic example from Ref. [15] (translated and modified), IWH = industrial waste heat, WI = Waste incineration, HOP = heat only boiler, CHP = combined heat and power plant.

2.2. Seasonal storage utilization and optimization

For enabling a significant supply of the above named renewable and low carbon heat sources, the surplus heat in summer times can be stored for transition or winter times, substituting at the same time fossil heat supply units. For this purpose, various large scale or "seasonal" storage systems are available, including aquifer, borehole, pit and tank storages, e.g. Refs. [16], [17]. Whereas numerous theoretical studies exist (e.g. Refs. [18], [19], [20], [21]), up to now, such systems have mainly been integrated in small/rural networks or building clusters in Germany, Denmark and Sweden focusing on solar thermal energy integration (e.g. Refs. [22], [23], [24], [25], [26]). Some cases for waste heat integration using seasonal storages have been theoretically investigated in (e.g. Refs. [27], [28], [29]) and only a few demonstration/implementation projects can be found (e.g. Ref. [30] and "anergy" or "ultra-low-temperature" DH networks utilizing various heat sources, e.g. Ref. [31]).

However, for larger, urban DH networks, seasonal storages have not been implemented so far. One very prominent example for an ongoing implementation project of a seasonal storage in an urban DH network is the city of Graz (Austria). Here, the current energy generation for the DH network is primarily based on fossil-fired CHP plants with an uncertain future perspective [32]. One supply option that is currently implemented are 450.000 m^2 solar thermal collectors supplying about 20% on the overall DH supply in Graz. Here, a key element is a seasonal storage with a volume of about 1,800,000 m^3 [33].

One of the main barriers for the integration of seasonal storages in urban DH networks is their high investment costs and the connected investment risk considering long payback periods. Here, production dispatching for multiple supply units allows a better utilization of the storage and therefore can play a central role in minimizing investment and operational costs. Therefore, several production dispatching tools are available at different time scales (from real or short term to long term management of production units) and implemented at several location scales (component, building, district or nation level) [34]. gives an exhaustive list of existing tools used at this scope and with focus on DH networks [35]. proposes a mixed integer linear programming (MILP) approach which enables the design of multi energy systems including seasonal energy storage systems [36]. focuses on the modelling of a solar system coupled with a seasonal storage in a dynamic modelling environment, where the sizing parameters were optimized through a Genetic Algorithm, showing improvements compared to other optimization methods by a pattern search [37]. investigates solar DH systems with seasonal thermal energy storage in different European countries and derives basic rules to achieve well working systems.

3. The case study Linz (Austria)

Linz is the economic and political center of the province Upper Austria. The city has about 192,000 inhabitants and therefore is the third largest city in Austria. It is characterized particularly by its large industrial enterprises. This is reflected also in the composition of the energy consumption. The share of coal at primary energy is 51%, the share of natural gas is 37%. Almost three quarters (72%) of final energy consumption in Linz is attributed to the industry. About 9% belongs to the sectors of service, transport and private households. Approximately 50% of the space heating demand is cover by DH. The final consumption of DH is around 20% to the industry, 40% to the services sector and 40% to the sector of private households. Around 59% of all apartments in the city are connected to the DH system [38], [39].

3.1. Status quo of the district heating system in Linz

The DH network of Linz AG spans most of the city and has two main plant sites "Linz middle" and "Linz south". A total of around 1130 GWh/a heat is generated by all plants of Linz AG. The base load is covered by a waste incineration plant, supplying ≈32% of the heat. About 14% is from a biomass CHP and approximately 47% is generated by fossil CHP plants (combined-cycle plant using natural gas). The fossil peak load boilers generate about 7% of the total heat demand. The heat losses in the network are about 7% of the heat input. The peak load heat demand in winter is about 500 MW and the summer minimum is around 30 MW. At peak load times about 320 MW are supplied by gas fired CHP plants. About 45 MW are provided from the waste incineration plant (also covering the summer heat demand) and the biomass-fired cogeneration plant supplies another 25 MW. The remaining ≈110 MW are supplied from fossil peak load boilers (oil and gas boilers), see Fig. 2. Further on, one short term thermal storage is located in "Linz middle", which supports the operation of the gas fired CHP plants and the

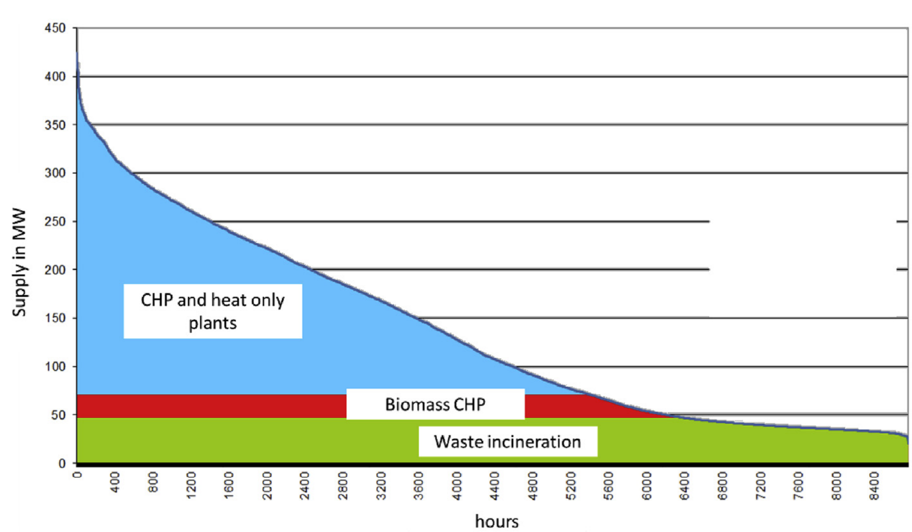

Fig. 2. Sorted load duration curve of the Linz DH network, data for 2012 [43].

waste incinerator. Sources for this section: [38], [40], [41], [42].

3.2. Potential waste heat sources in Linz

Based on interviews and workshops with different local companies, industrial partners and stakeholders, a conservative assumption of available waste heat potential of around 55 MW in the summer months and 40 MW in the winter months is made. The main waste heat source are high temperature processes in a steel mill at a temperature level of >130 °C, as well as heat from flue gas condensation including a heat pump boosting the temperature to the necessary level. Therefore it can be used in the network directly without the need of another temperature boost.

However, due to the need of a constant operation of the waste incineration plant throughout the whole year (must-run-condition, except 4 weeks of fixed maintenance during autumn), there is no possibility to integrate additional heat supply during summer times (see also section 2.1). Already there is a small over production from the waste incinerator for limited times during the summer period. Since the exiting short term storage reaches its limits after a few hours, further heat supply would require a seasonal storage.

3.3. Preliminary study on a seasonal storage design

In a preliminary study [44] (see also [45]) technical details (hydraulic integration concepts, storage design, etc.) of a seasonal storage for Linz were investigated. The resulting design and main characteristics are summarized as follows:

- storage size: 80 GWh (≈2 million m^3)
- storage type: pit storage
- location: at the power plant site Linz middle
- Investment costs: about 100 mil. Euro

Although the preliminary study considers ground water as a heat source via a heat pump, the boundary conditions and data for the seasonal storage are used in the actual study as basis for further investigations.

4. Methodology

The following methodology for find the optimal integration and operation of the seasonal storage has been used, see Fig. 3.

4.1. Modelling of the DH network

Heat supply: At the starting point the existing measurement data of the main supply units are analyzed and implemented to calibrate the models and control strategies (priority settings). Subsequently, different operation strategies (see section 4.2) for the individual scenarios (see section 5.1) are developed, which led to an optimized operation of the system, including waste heat and a seasonal storage. These optimized control strategies are included in the supply models in the following iteration step, to generate an overall optimized system operation.

Network: Data from the network operator were adapted to the requirements of the project as in the scenarios described, focusing on the hydraulic limitations (see section 5.1). The dynamic thermo-hydraulic behavior of the DH network is represented with numerical models of the partially simplified and/or aggregated DH systems developed in Modelica/Dymola [46] [47], based on models of the Modelica Fluid library [48], Buildings library [49] and on the DisHeatLib [50] developed at the Austrian Institute of Technology. Those libraries include models of producer units, hydraulic schemes of substations, building models and preconfigured pipe models. Based on the simulation results, energetic (primary energy consumption) and ecological indicators (CO_2-emissions) for the different scenarios were calculated.

Consumer: The consumers are modeled in a simplified way into the network model. The heating load results from the combination of space heating and domestic hot water preparation. The space heating is based on the Modelica Resistance-Capacity-Model, and is parameterized with the building physics properties from the project Tabula/Episcope [51]. The domestic hot water model was

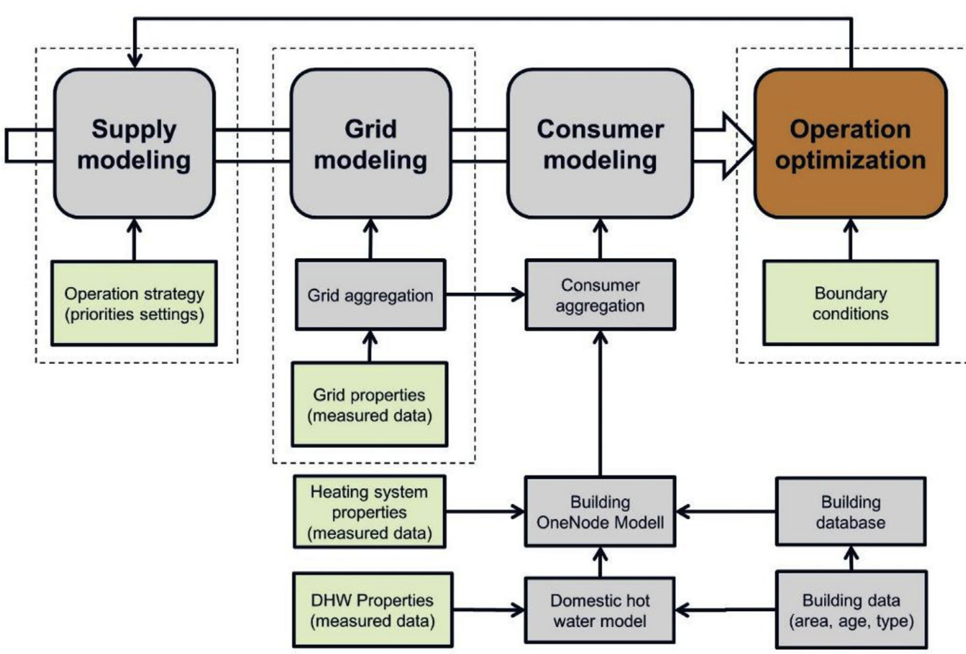

Fig. 3. Methodology of modelling and simulation.

additionally calibrated with Monitoring data from previous projects, described in Refs. [52] and [53]. The aim of the dynamic network simulation was the determination of heat and temperature distribution in the network to discover possible bottlenecks (sections with hydraulic limitations) and locations where further measures are needed to guarantee a sufficient heat supply. Also the distribution of return temperatures was analyzed due to possible effects on the storage performance and capacity.

Validation of key components and comparable settings of DH networks have been performed for building models [53], [54], substation models [55], pipeline models ([48], [56]) and network aggregation method [57]. A detailed error propagation methodology and commonly recognized test cases for validation of dynamic DH network simulation environments do not exist in the scientific community and therefor have not been performed. However, a common test case standard for Modelica models is going to be developed within the framework of the IEA EBC Annex 60 [58].

4.2. Operation optimization

The results of dynamic supply, network and consumer simulation were used as input parameters for the operational optimization. This includes the optimized scheduling of the existing plants as well as the optimal storage management. The task is handled as a “unit commitment problem”. This is especially suitable in this case study, since typical decisions made in unit commitment problems involve for example on hourly basis:

- Whether production unit is producing energy or not?
- How much energy should a unit produce?
- How much energy should be fed to the network or to available storage?

The model is based on the mixed integer linear programming (MILP) method. The MILP method is very suitable for solving unit commitment problems due to their flexibility in addressing the trade-offs between system accuracy and the robustness of the optimization solution method, especially in the absence of uncertainty (for example in demand or energy prices) which is the case here [59], [60].

The model provides the cost optimal operation strategy of a set of district energy system components. This means it finds the cheapest solution for operating thermal and power plants, alternative energy sources and storages at every time step over the optimization period. It also allows prioritization of different supply components if needed by adding weighting factor to the relevant variable in the objective function. Different components, mainly power plants and storages, are imported exogenously to the model in the form of component specific data. For power plants the data consists of nominal capacity, thermal and electrical efficiency, minimum partial load operation of plants, plant ramp-up rate, carbon dioxide factor and operation and fuel cost. In case of storages the data consists of storage capacity, maximum charging and discharging rate, thermal loss factor and minimum state-of-charge. As the model is linear it simplifies the non-linear reality of some system properties, for example the non-linear relationship between efficiency of heat and power plants and their partial load operation. This is a necessary trade-off in order to achieve robust (that is best possible) solution. The binary feature of MILP is especially useful for dealing with the scheduling issues of different system components and accommodating on/off function of the available components. That is done by establishing binary variable that defines for example the on/off state of plants or control strategy of storages.

The model is formulated as a set of linear algebraic equations representing component interactions and together they govern the energy flow between components as well as the operation behavior. These equations are composed of decision variables defining fuel consumption, heat generation, power generation, storage state of charge, storage charge and discharge etc. The solution of the decision variables is determined by an optimization solver according to data signals such as time series of heat demand and cost parameters and component specific operation boundaries. The objective function to be minimized is formulated as summation of the multiplication of cost parameters and decision variables as so:

Equation 1: Objective function

$$\min \sum_{j=1}^{n} c_j \cdot x_j$$

with c_j denoting cost parameter to a corresponding decision variable x_j. The objective function is the total system operation cost over the time span of a year, representing the operational cost of heat and power plants associated with the heat and electricity generation. The system constraints can be represented with the following generalized linear model.

Equation 2: System constraints

$$\sum_{j=1}^{n} a_{ij} \cdot x_j = b_i \quad (i = 1, 2, \ldots, m)$$
$$x_j \geq 0 \quad (j = 1, 2, \ldots, n) \quad x_j : binary \quad (for\ some\ j = 1, 2, \ldots, n)$$

a_{ij} is a multiplication coefficient of decision variable x_j. The form of the first equation applies to all the linear constraints, together generating space of feasible solutions of decision variables. This solution space then guides the objective function to find the optimal outcome.

The model was implemented in Matlab and executed using the intlinprog solver. Fig. 4 shows exemplified results of the operation optimization simplified for one day.

Considering the limitations from computational capacity, the optimization problem, which is solved for a whole year is split into smaller optimization problems that are run recursively throughout the year. Constraints on the charging and discharging level for the seasonal storage have been pre-defined for the whole year in order to be ensure an optimal yearly solution. To ensure continuity in the daily solutions, the initial values of the optimization for day i are the

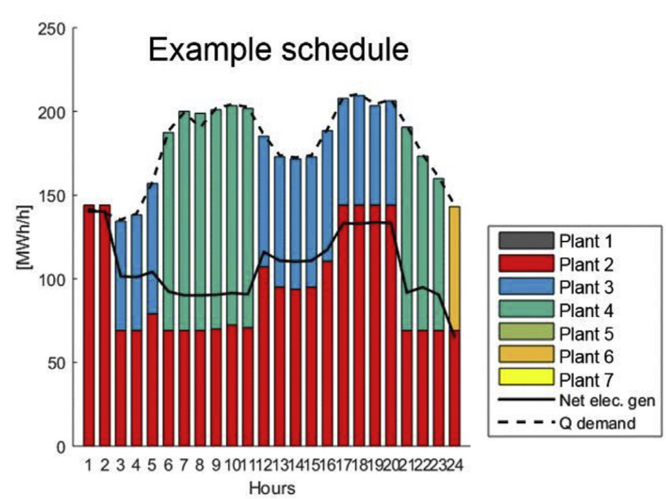

Fig. 4. Exemplary results of the operation optimization.

final values of the optimization of the previous day (i-1). In this case, the optimization is performed over 48 h, but only the first 24 h are stored (see Fig. 5).

The methodology above is used to develop an optimized operation strategy for all developed scenarios in order to achieve minimized operation costs.

5 economic assessment: To generate an optimal solution in terms of total and life time cost, an additional economic assessment is carried out using the simulation results. Therefore innovative investment concepts, possible funding schemes and a micro- and macroeconomic evaluation are performed. The methodology and results of the organizational, business economic and macroeconomic analysis of the Linz seasonal heat storage are discussed in Ref. [61].

5. Scenario description and technical simulation

For the evaluation of the different supply situations in the interaction with the waste heat and the seasonal storage, the following four relevant scenarios have been developed in workshops with project partners and stakeholders, also considering the results from section 3.3. A scenario with waste heat integration, but without the seasonal storage was dismissed by the stakeholders for economic reasons.

The waste heat is assumed to be always provided at the temperature level which is required in the network, resulting from the specifications of the industrial process. Moreover, due to the existing plant portfolio based on fossil heat plants, it is assumed that it is always possible to boost the heat from the storage, which is limited to a maximum of 97 °C, to the needed network temperature by mixing with other supply units (the flow rates in the model are adjusted accordingly).

5.1. Scenario description

In this section the scenarios are described and compared to the status quo of the DH system in Linz. In Fig. 6 the scheme of the simplified DH network the differences in the network and generation units in each scenario are shown. It is important to highlight that heat from the various supply units can be injected directly to the network or stored into one of the storage units with the exception of the heat pump which can inject only into the seasonal storage system with a constant supply temperature of 97 °C. The scenarios are summarized in Table 1.

This scenario corresponds to the current state of the DH system of Linz AG. The set-value of the supply temperature in the network is depending on the outdoor temperature, between 130 °C and 80 °C. The return temperature is about 60 °C on average, see Fig. 7 and Fig. 8.

There are following hydraulic limitations, limiting the maximum flow rate: In “Linz middle” a maximum flow rate of 4500 t/h and in “Linz south” a maximum flow rate of 2500 t/h of DH water is possible in the supply line.

Based on the stakeholder discussion, the reduced heat demand in the network due to continuous thermal retrofitting of the customers is balances with densification of the network, i.e. connection of new customers that have not been connected to the networks before.

5.1.1. High temperature scenario (HT)

In addition to the existing heat plants, waste heat from the industrial process of the steel mill is feed into the DH network as well as recovered heat from the exhaust gas of existing heat plants, using a heat pump for flue gas condensation. To integrate the available waste heat into the system, the described seasonal storage with a capacity of 80 GWh (maximum storage temperature = 97 °C) is integrated into the simulation models. The linearization of the seasonal storage included different simplification: no stratification and constant value of the heat losses (regardless of the storage level). Due to the ratio of storage surface to volume, heat losses are relatively low (based on an average state of charging and average outdoor temperatures losses of 1 MW are assumed). Heat pumps for discharging the storage below the return temperature are not considered based on the stakeholder discussions.

5.1.2. Low temperature scenarios (LT)

Current developments in DH systems show a clear trend towards lower system temperatures [63]. Following this trend, also low-temperature scenarios are investigated. Here, the network is assumed to have the same topology, only the temperatures are changed. Supply temperature set-point is reduced from 130 °C to 97 °C (at peak load conditions) and return temperatures to about 50 °C. Although those are still relatively high temperature levels compared to the 4th generation of DH network, they are required to satisfy the specifications of the storage units (not pressurized storage) and the limitations from existing pipeline design. Lower return temperatures are considered to be challenging from the network operators point of view. The efforts for the required modifications/optimizations on the consumer side substations and heating systems are neglected in this analyses. Thus, those scenarios cannot be implemented without further ado. However, continuous network developments and optimization might lead to the assumed temperatures sooner or later.

Due to the lower system temperatures, the efficiency of the heat pump can be improved. However, in all investigated scenarios, a condensing temperature of 97 °C was considered (see section 4.1.2). Although the return temperature is reduced by 10 K, the effect on the COP of the heat pumps is insignificant, so it was not included.

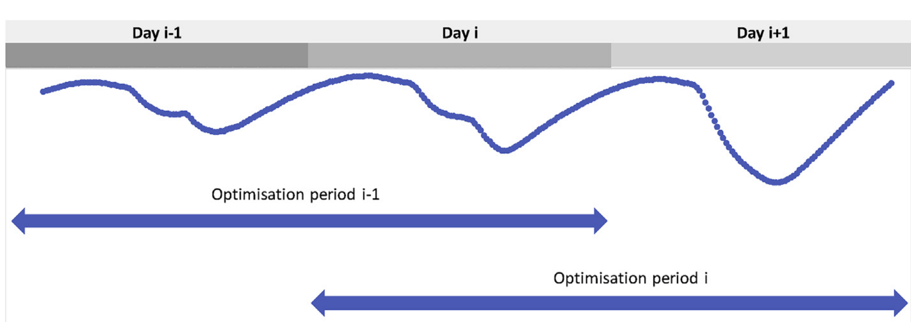

Fig. 5. Optimization process: rolling horizon.

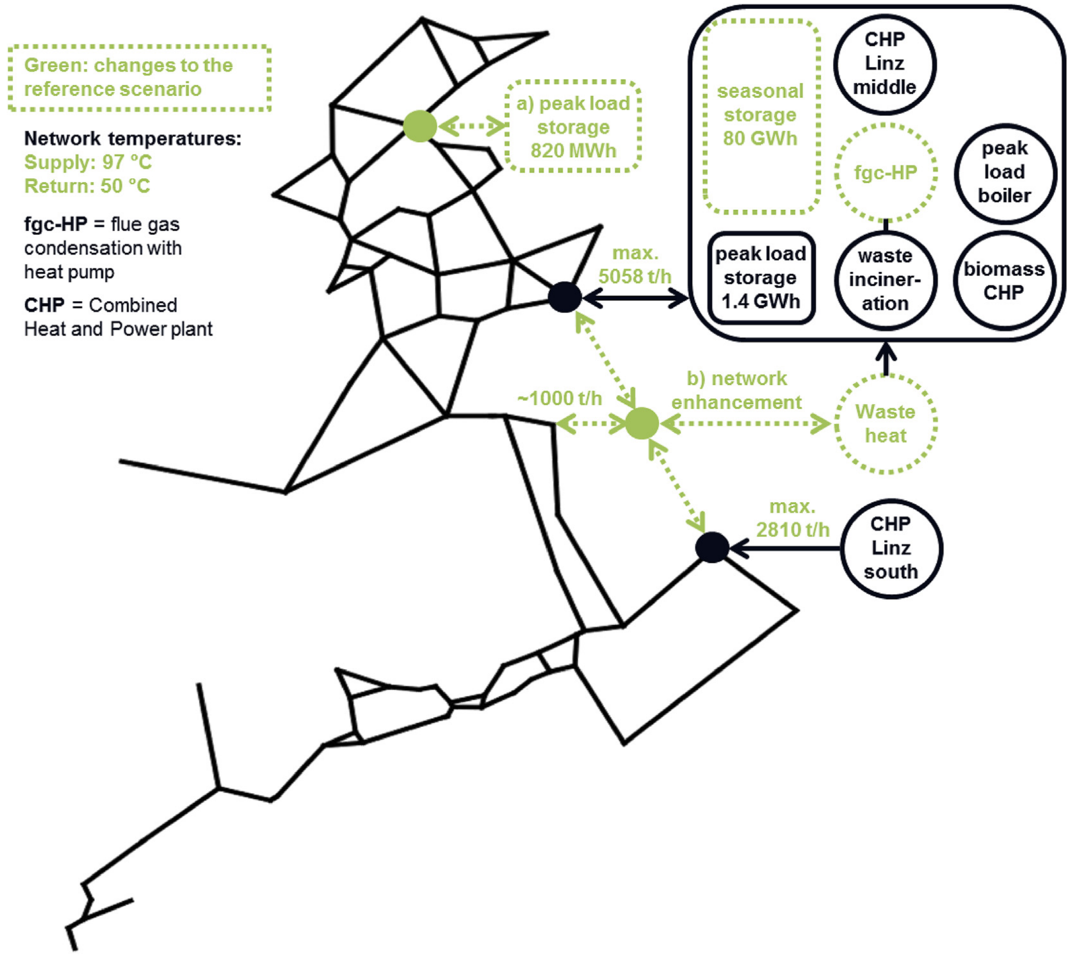

Fig. 6. Scheme of the simplified DH network and differences in the scenarios (green colour and dashed lines); the seasonal storage, the fgc-HP and the waste heat are in all scenarios except the reference scenario included. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Scenario overview.

Scenario	Network Temperatures		Max flow rates		Storage capacities	
Reference scenario	Supply:	80–130 °C	middle:	4500 t/h	existing DH storage:	1.4 GWh
	Return:	≈60 °C	south:	2500 t/h		
Scenario HT	Supply:	80–130 °C	middle:	4500 t/h	existing DH storage:	1.4 GWh
	Return:	≈60 °C	south:	2500 t/h	Seasonal storage:	80 GWh
Scenario LT + peak storage	Supply:	80–97 °C	middle:	5058 t/h	existing DH storage:	1.4 GWh
	Return:	≈50 °C	south:	2810 t/h	Seasonal storage:	80 GWh
					Peak storage:	0.82 GWh
Scenario LT + network enhancement	Supply:	80–97 °C	middle:	5058 t/h	existing DH storage:	1.4 GWh
	Return:	≈50 °C	south:	2810 t/h	Seasonal storage:	80 GWh
			New point:	1000 t/h		

a) Reference scenario.

Further on, lower system temperatures modify the hydraulic condition in the network. I.e. the maximum flowrates can be increased to 5058 t/h in “Linz middle” and 2810 t/h in “Linz south”. Nevertheless these changes are too small to balance the reduced heat transfer due to the reduced temperature difference between supply and return temperature. Hence additional measures are needed to avoid bottlenecks in the network and guarantee a sufficient heat supply in the whole systems (additional peak load storage and network enhancement).

5.1.2.1. Low temperature scenario + peak load storage (LT + peak load storage). In this scenario, an additional decentralized peak storage is integrated into the network to compensate peak loads and thus reduce the maximum required flow rates at the supply points. An analyses of the measured data and the simulation results shows, that in the north of the network a thermal storage with a capacity of about 820 MWh would be necessary in order to meet the network restrictions.

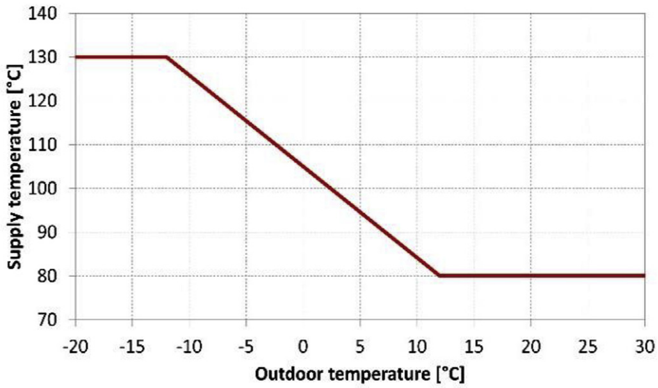

Fig. 7. Set-value of the supply temperature [62].

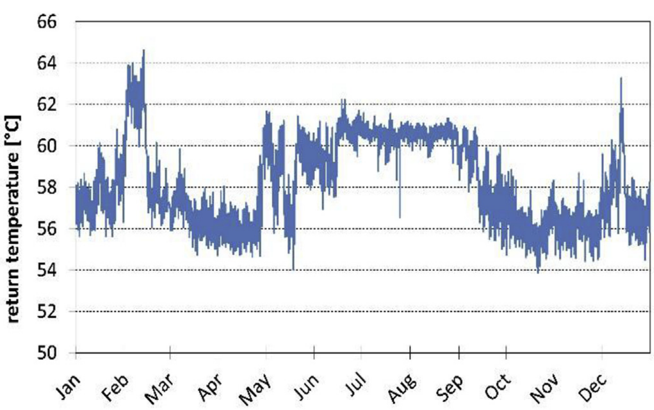

Fig. 8. Measured return temperature [62].

5.1.2.2. Low temperature scenario + network enhancement (LT + network enhancement). Compared to the scenario "LT + peak load storage", the network is now enhanced by integrating an additional pipeline from CHP south to Linz middle in order to avoid the limited flow rates at the existing supply points. As a consequence, an additional supply point with 1000 t/h is generated. Therefore, the plant operation can be more flexible since all producers are connected and can supply heat to all supply points.

5.2. Operation optimization

For the operational optimization of the supply units and the storages in the DH system of Linz AG (as described in section 4.2), following initial priorities are implemented:

1. Waste incineration plant
2. Waste heat from industry
3. Flue gas condensation by heat pump
4. Biomass CHP
5. CHP middle
6. CHP south
7. Peak load boiler

This basic order was determined under static conditions. Thereby averaged production costs and the respective heat production costs are determined. During the operation optimization (optimized heat plant scheduling) this order is recalculated for every hour of the year, based on the respective framework conditions (energy prices, efficiency, heat demand, network restrictions, etc.) and the most favorable generation variant is selected. However, due to the must-run-condition of the waste incinerator, it is always considered as priority 1.

The optimization model was executed for two different scenarios of operation strategy of the seasonal storage: a) simple operation and b) strategic operation. Under scenario a) the storage is operated under normal non-incentivized conditions. That is, it is available for the whole year but its function is mostly limited to store the available waste heat during summer time for later utilization in fall and winter. Under scenario b) the usage of the seasonal storage is incentivized by assigning a strategically selected weighting factor, to test if the fossil fuel consumption and dependence on specific heat plants can be reduced by encouraging the seasonal storage utilization. This extends the usage of the storage beyond the seasonal function, encouraging also short term operation of the storage and increasing flexibility of the system supply management.

5.3. Boundary conditions and assumptions

With the defined network restrictions and the assumed framework conditions of the system an optimized planning of the plant park including waste heat integration and storage management was then determined. The parameters used are shown in the Tables 2–6 below.

Since the electricity sales are a key factor for the operational optimization of the CHP, data from the EPEX DE-AT Spot Market [65] from the year 2015 are defined as electricity prices within this project. In the strategic storage operation, based on the cost and demand developments, also strategic decisions are made, if the seasonal heat storage is loaded at certain (high-price) times in order to meet future demand (at low-price times). The prices in the respective hours are shown in Fig. 9.

Table 2
Heat plant specifications.

Plant name	Fuel	Nom. Cap[a] [MW]	Heat cap[a] [MW]	Electr. Cap[a] [MW]	Electr. Eff.[a]	Total eff.[a]	Min load operation[b]	Heat ramp-up limit[c] [MWh/h]	CO_2-factor Fuel [t_{CO2}/MWh_{th}]
RHKW	Waste	68	45	15	22%	88%	50%	22.5	0
Biomass	Wood chip	38	25	8	21%	87%	20%	10.0	0
CHP middle	Gas	452	171	227	50%	88%	35%	59.9	0.22
CHP south	Gas	368	150	170	46%	87%	35%	52.5	0.22
Peak boiler	Gas	121	111	0	0%	92%	20%	38.9	0.22
Waste heat	Waste heat	40	40	0	0%	100%	0%	40.0	0
FGC-HP	Electricity	2,7	15	0	0%	550%	0%	15.0	0

[a] [64].
[b] The minimum ratio of the heat capacity that the plant can operate.
[c] The maximum thermal power ramp-up potential of the plant in 1 h.

Table 3
Cost assumptions.

Plant name	O&M cost [EUR/MWh]	Fuel cost [EUR/MWh]	Sold electricity
RHKW	−10.00[b]	0	[65]
Biomass	3.00[c]	30[c]	95 [EUR/MWh][c]
CHP middle	3.48[c]	38[a]	[65]
CHP south	3.48[c]	38[a]	[65]
Peak boiler	39.34[b]	38[a]	–
Waste heat	−5.00[b]	0	–
FGC-HP	15.0[d]		–

[a] Preliminary value.
[b] Cost number adjusted for prioritization purposes.
[c] [64].
[d] [65].

Table 4
Storage assumptions.

Storage type	Capacity [MWh]	Max. In-/ output [MWh/h]	Heat losses [MWh/h]
short term storage	10	100	0,2
Seasonal storage	80000	250	1
Peak load stage	820	100	0,1

[64] and simulations results for peak load storage.

Table 5
CO2 and PEF assumptions.

Plant name	CO_2 [t_{CO2}/GWh_{th}]	Primary energy factor [–]
RHKW	18,3[a]	1,02[a]
Biomass	10,6[a]	1,06[a]
CHP middle	317,0[a]	1,60[a]
CHP south	270,9[a]	1,37[a]
Peak boiler	259,0[a]	1,31[a]
Waste heat	23,1[a]	1,00[b]
FGC-HP	50,2[b]	0,35[b]

[a] [66].
[b] [15].

Table 6
Overview of fundamental assumptions.

Cost and income category	Remarks	Effective in year
Investment costs	Construction, property, associated equipment (pipes and pumps)	t = 0
Investment costs	Filling the storage with deionized water, including well drilling and additional processing plants	t = 1
Operating costs	Pump electricity, heat losses, insurances, residual maintenance	t = 3 … n
Revenues	Volume-weighed, time-dependent price (estimated value based on [15]) of thermal charged and discharged energy.	t = 3 … n

6. Results

6.1. Simple vs. strategic seasonal storage operation

Simple operation strategy: The main task of the seasonal heat storage is to shift the industrial waste heat (as well as small amounts of the excess heat from the waste incineration plant) from summer to autumn or winter period. Additionally the storage can be operated at high peak load times (bottlenecks) or at times with very high electrical energy market profits of the CHP plant but low heating demand, typically during the transitional period (see Fig. 10). It is, however, also shown that the seasonal storage is charged and discharged at short notice. This resulted in a total charging and discharging or supplying into the network form the storage of 143 GWh. This corresponds to ≈1.8-fold storage capacity (1.8 storage cycles).

Strategic operation strategy: Based on the simple storage operation strategy, the seasonal storage is integrated into the plant schedule. This is done as described in section 5.2, whereby the seasonal storage is also operated as a short-term storage for a "strategic" operation. The integration of the seasonal storage also as short-term storage allows a more frequent charging and discharging during winter and transitional period (see Fig. 11). Thus a

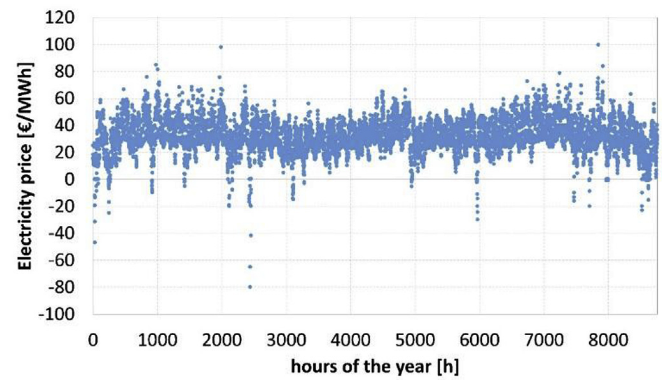

Fig. 9. Electricity price EPEX DE-AT Spot Market 2015 [65].

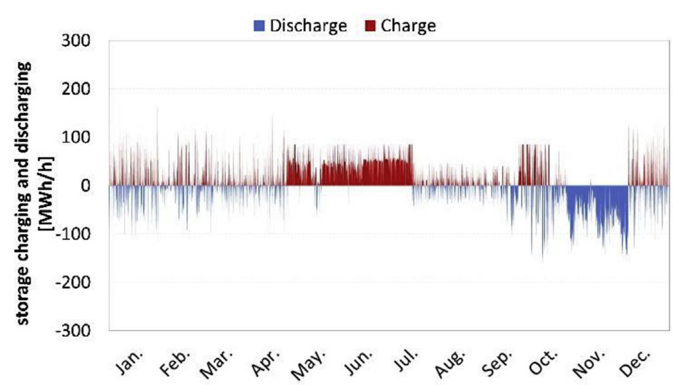

Fig. 10. Charging and discharging of the seasonal storage with simple storage operation.

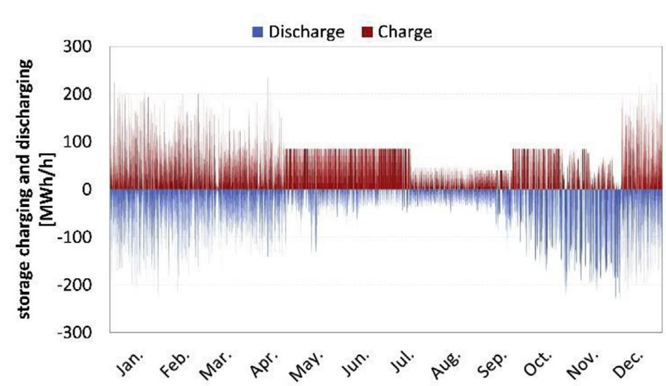

Fig. 11. Charging and discharging of the seasonal storage with strategic storage operation.

total of ~348 GWh could be stored or can be supplied from the storage into the network. This corresponds to ≈4.4-fold storage capacity (4.4 storage cycles).

Figs. 10 and 11 show the charging and discharging behavior of the two different strategies from the Scenario HT. In the further simulations only the strategic operation was used for the seasonal storage.

6.2. Scenario comparison

Load curve: The comparison of the load duration curves of all considered scenarios is shown in Fig. 12. It can be seen, that in the reference scenario in winter times both the CHP south and middle are operating as well as the peak load boilers. In all scenarios with seasonal storage, the waste heat is utilized until 4750 h, than the storage is fully charged. A larger storage could be used to utilized higher amounts of waste heat, however, this has not been investigated since detailed characteristics of were not available. The discharging begins as soon as the heat demand is larger than the supply from the waste incinerator and the waste heat. In the scenario LT + network enhancement, the supply from the CHP plant south, that has with lower efficiency and higher costs is reduced significantly, since the additional piping allows the CHP middle with a higher performance to supply also to the southern parts of the network.

Yearly values: The comparison of the resulting yearly heat supply (Fig. 13) shows that due to the waste heat from the industry and the FGC-HP, heat from fossil plants like the CHP as well as the peak boiler can be reduced. However, the integration of the waste heat also substitutes the biomass plant for certain times in the year. The general amount of waste heat supplied is approximately constant. Due to storage losses, slightly more heat is required in the HT scenario than in the reference scenario. In the LT scenarios, the storage losses are balanced by lower network losses caused by the lower system temperatures.

The fuel/energy demand can be reduced by 21% when

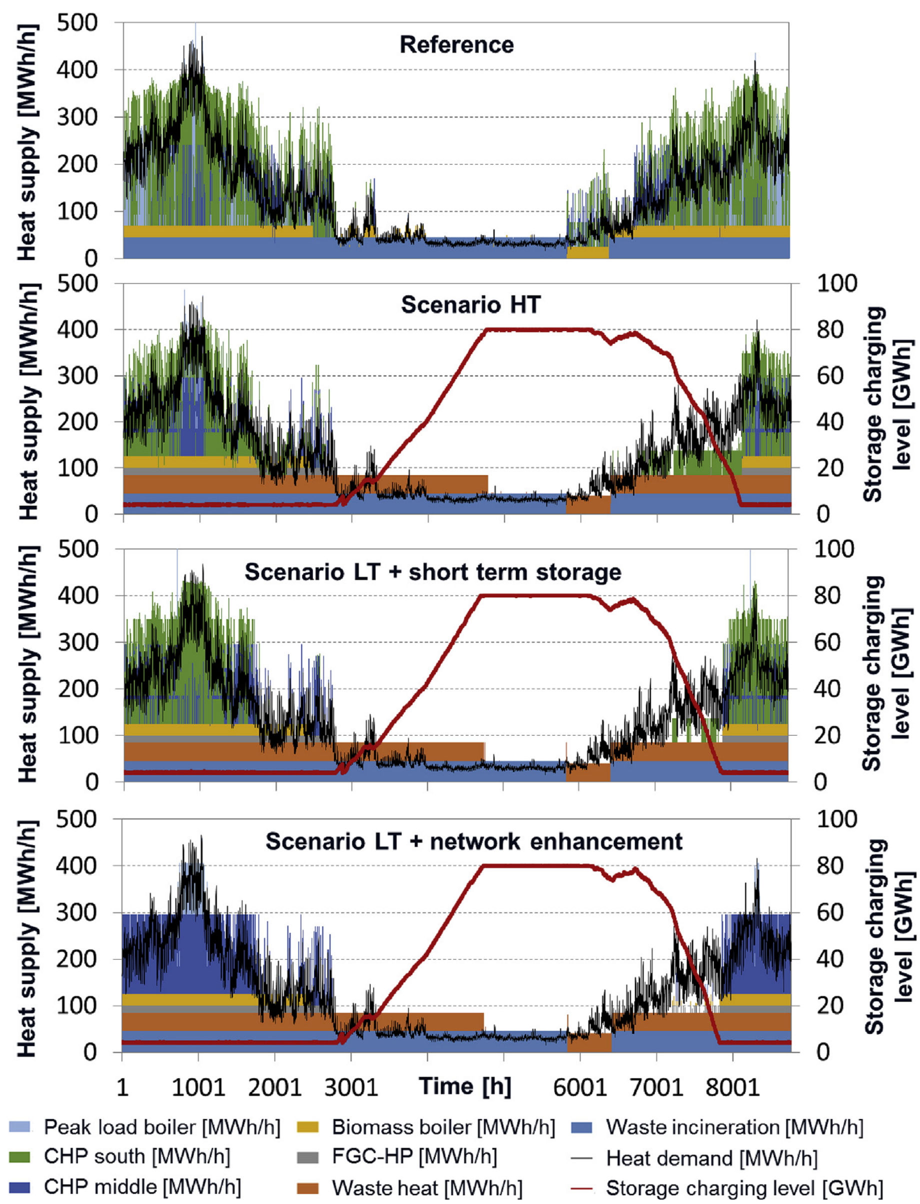

Fig. 12. Load curves of all considered scenarios.

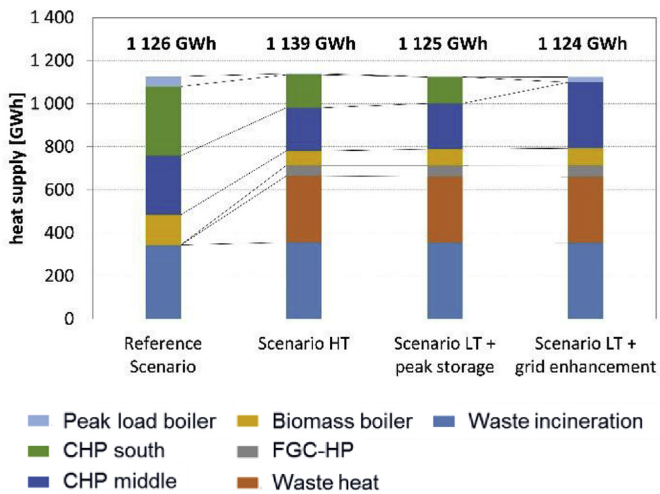

Fig. 13. Heat supply comparison.

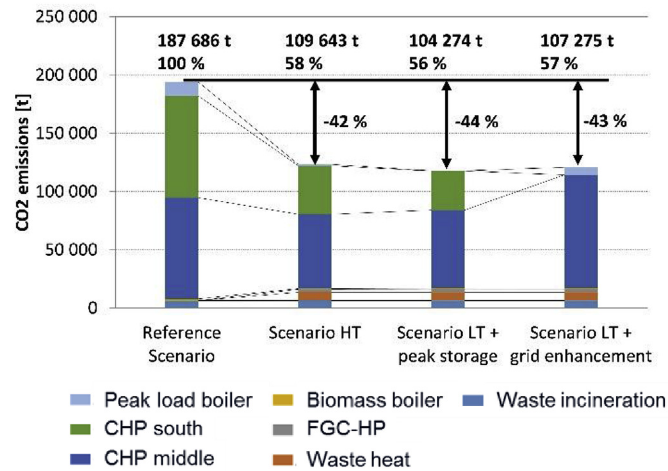

Fig. 15. CO2-Emission comparison.

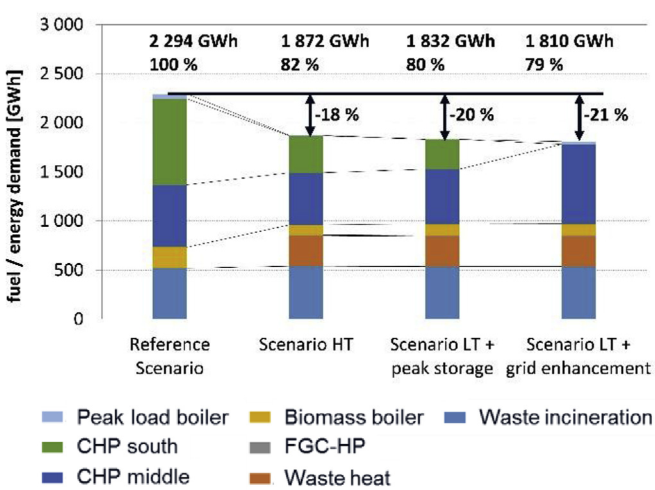

Fig. 14. Fuel/energy demand comparison.

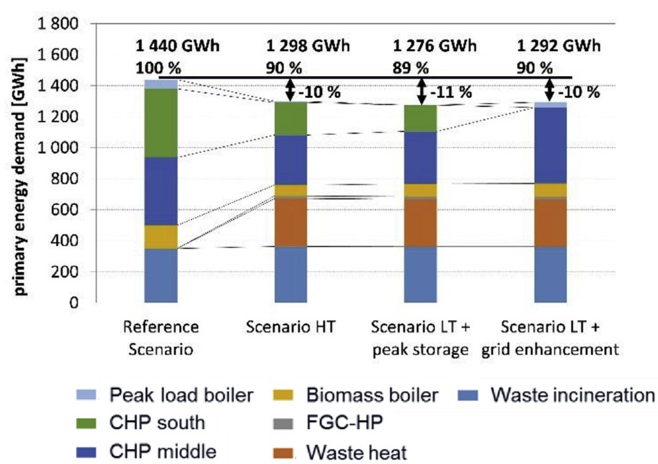

Fig. 16. Primary energy demand comparison.

integrating waste heat, as shown in Fig. 14 and the CO_2 emissions can be reduced significantly up to 44%, as shown in Fig. 15. The efficient use of existing waste heat sources and the highly efficient heat pump is also reflected in a reduced primary energy consumption. This could be reduced by around 10% in all scenarios (Fig. 16).

7. Economic effects

7.1. Assumptions

It is assumed, that the storage operator is an independent company, i.e. the storage operator optimizes its charging and discharging processes without any non-market preference for a certain source of energy. However, the analysis showed that results would be the same if the DH company is the operator of the storage.

The *investment costs* for the construction of the storage, associated equipment (pipes and pumps) as well as the property have been selected based on [45]. The resulting investment costs are approx. 106.5 million Euro. As the storage should be situated close to the main CHP site “Linz Middle”, a suitable property in the city's industrial area worth 17 million Euro is included. Approx. 70–80 million Euro are construction costs. The total investment costs were assumed to be due in year t = 0. As the storage contains 2 million m^3 deionized water, the filling takes approx. nine months conducted in year t = 1.

The *operating costs* include expenditures for pumping electricity, heat losses, insurances, maintenance (e.g. appearance of the envelope or equipment) and legal assessments. Based on experts' estimates, cost of 0.7 million Euro per year is assumed. Due to the lack of experience with storages of this size and type, significant fluctuations in the calculated costs may occur. Note that the storage is designed to operate without any significant maintenance for years: as the filling of the storage takes approx. nine months, comprehensive maintenance requiring emptying the storage are to be avoided, as it would interfere with the operation for a significant time and would have a negative influence on the amortization period. Heat losses are economically relatively irrelevant as applied costs are the costs of charging energy which is waste heat and thus is only approx. 30,000–100,000 Euro/a, depending on the method of cost allocation. Costs of the again-delivered charging energy are included as a negative parameter in the calculation of revenues.

Revenues are generated through hourly, daily and monthly (= seasonal) shifts of the thermal energy, which are achieved by charging the storage at favorable prices (predominantly with waste heat from industrial processes in summer months or electricity production in the CHPs) and by discharging at elevated prices (especially during heat-driven operation of the CHP). Using the economic "heat merit order" tool (see Ref. [15]) annual revenues (i.e. attributable savings) of approx. 9.6 million Euro are achieved, assuming constant real mean market prices of gas, electricity and CO_2 (EU emission trading scheme). A discount rate of 5% is assumed.

7.2. Results

Based on the above assumptions, the calculated amortization period of the proposed seasonal storage for Linz is 20 years of operation. The calculation does not include any subsidies from the European Union, federal, regional or local governments. From the economic analysis, the following main results can be derived:

The cost-effectiveness is essentially influenced by the annual storage throughput (*charging cycles*), i.e. how often the store is (partly) charged and discharged per year. Under the assumed energy and carbon market prices, a storage operation limited to seasonal charging/discharging is economically infeasible. Using the storage tank in order to optimize power plant dispatch is crucial for storage throughput (i.e. charging cycles) and economic feasibility.

The analysis shows a large *sensitivity* to the electricity, gas and CO2 market prices (EU emission trading scheme). Thus, economic uncertainties i.e. risks are crucial for understanding and rethinking the above-mentioned payback period.

Neglecting economic and technical risks, a payback period of 20 years makes the investigated seasonal storage an interesting topic for *further research* and market-oriented technical improvements.

8. Conclusions & outlook

Within the DH network of Linz, available industrial waste heat cannot be supplied during summer times due to the must-run condition of the waste incineration. A pre-study analyzed possible locations, geometries and costs of a seasonal storage for the Linz DH network (based on ground water heat as heat source). As a result, a volume of 2,000,000 m^3 (80 GWh) with investment costs of about 100 mil. € has been chosen. Within this study, different scenarios for the integration of the waste heat into the Linz DH network via the seasonal storage have been analyzed. A scenario with waste heat integration, but without the seasonal storage was dismissed during a stakeholder workshop for economic reasons.

Since the number of charging cycles is crucial for economic feasibility, two different strategies have been investigated: The "simple" charging strategy, where the storage is mainly charged in summer times using industrial waste heat and discharged in autumn/winter is resulting in utilization a 1.8-fold storage capacity. In this case, the revenues are always too low for reaching economic feasibility. For the "strategic" operation strategy, fostering a much higher degree of short term charging/discharging and as a consequence enhancing the operation of the existing CHP plants and reducing the use of the peak load boiler, this value is increased to 4.4. As a result, a payback period for the seasonal storage of about 20 years (ideal case) can be achieved. In this analysis, various uncertainties apply (electricity prices, long term availability of the waste heat and CO2 market conditions) and together with the high investment costs of about 100 mil. Euro, the investment risk for the storage is very high in the particular case. However, smaller DH networks with lower network temperatures and lower investment costs have already proven to be realizable.

On the ecological side, about ¼ of the energy in the Linz DH network can by supplied by waste heat if integrating a seasonal storage, substituting especially fossil fired CHP and peak boilers, resulting in up to 44% reduction of CO2 emissions. Low temperature scenarios could bring benefits such as a smaller storage size with the same capacity. However, in this case, additional measures are required for supplying all customers due to hydraulic limitations (additional short term storages or network extensions) that are not considered in the economic evaluation.

Nevertheless, the integration of seasonal storages is a key element for future-prove DH networks since it supports the utilization of other alternative heat sources such as heat pumps, geothermal and solar thermal energy that otherwise are in competition in summer times [67]. For facilitating the integration in urban DH networks, further work needs to be done, especially in following areas:

- Optimized planning, design and operation of the storage, considering the different energy vectors (heating, cooling and electricity), multiple purposes for the storage and all available energy sources (including e.g. solar energy).
- Further optimization of the seasonal storage charging and discharging strategy. The current optimizer considers only 3 days in a row and thus resulting in a non-optimum discharging already in the transition period. A longer time frame in the optimization would allow the storage to discharge in winter times, resulting in a higher economic and ecologic performance.
- A sensitivity analysis of the main parameters (especially electricity price scenarios and investment costs) for a detailed assessment and management of the risks connected with the investment into the storage.
- Further development, optimization and demonstration of seasonal storage technologies for urban DH networks and related materials (e.g. optimizing the lifetime of materials especially at higher temperatures, analyses of the detailed costs and concepts for lining and construction), including heat pump integration.

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