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Energy System Benefits of Combined Electricity and Thermal Storage Integrated with District Heating

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ABSTRACT

In the development towards smart and renewable energy systems with increasing supply of electricity from fluctuating sources there is an increasing need for system flexibility. In this context the role and need for grid-level electricity storage is debated. Ideally, there would not be a need for storage, but the alternative system flexibility solutions may not cover all the flexibility needs, which will leave a potential for the storage of electricity. In this study, a compressed heat energy storage (CHEST) is assessed. It combines electricity and thermal storage in one system and can simultaneously benefit electricity and district heating (DH) systems. In a technical energy system analysis with the energy system of Germany as a case, a CHEST system is analyzed in different configurations with and without DH integration. The results indicate that electrochemical storage is more effective than CHEST if DH integration is not present. However, if DH integration is assumed, the CHEST technology can be more effective in reducing the primary energy supply. This applies, however, only for DH systems based on electrified heat sources, whereas in DH supplied by combined heat and power plants and fuel boilers, the CHEST system do not show more effective.

Keywords

Energy storage;
District heating;
Carnot battery;
Energy system analysis;
Renewable energy;

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1. Introduction

In the development towards a smart and renewable energy systems, there is an increasing supply of electricity from fluctuating sources and at times the production exceeds demand which results in the curtailment of excess electricity production in critical hours. Curtailment is a lost opportunity to replace other forms of energy use, e.g. fuel consumption in a thermal power plant (PP). At other times with excess production, the excess electricity may be exported, avoiding curtailment, however often at a low price. Here, the excess electricity is a lost economic opportunity because the electricity might have been used more efficiently. The challenge of excess electricity can be expected to grow in the future and the need for efficient solutions will continue to grow as well [1].

1.1. System flexibility measures

Various solutions can contribute to balance supply and demand of electricity, which in the following are referred to as flexibility measures [2]. These can be seen in many places already today, for example in mountainous regions, where rivers are dammed to release the water through turbines when there is a demand, or pumping water back into the dam using excess electricity, and there by storing it for a time with a demand [3]. This technology has worked for several decades but is in the current development gaining additional value for balancing of demand and supply of fluctuating renewable sources of electricity production [4].

Other flexibility measures are also emerging as solutions to the challenge. Flexible demand of electricity at the consumer side can be an option of how to move

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Abbreviations	
CHEST	Compressed heat energy storage
CHP	Combined heat and power
COP	Coefficient of performance
DH	District heating
EEP	Excess electricity production
HP	Heat pump
ORC	Organic rankine cycle
PES	Primary energy supply
PP	Power plant
PV	Photo voltaic
RES	Renewable energy source
TES	Thermal energy storage

demand to times with excess electricity from times with less renewable electricity [5]. This could be a laundry machine able to postpone its start during a night based on a signal from the electricity market [6]. Another potential solution is to have battery electric vehicles being able to postpone a share of the needed charging time flexibly during the night [7]. In addition, the battery of the electric vehicle could supply power back into the electricity grid at a time of need for balancing support at the grid level. A third flexibility measure can be to couple the electricity sector to DH though flexible units that can operate on both markets, e.g. combined heat and power (CHP) or heat pumps (HP) [8]. Another option, that is still in development and demonstration, could be to produce hydrogen using electrolysis to consume electricity at times of excess production and store the hydrogen for later use [9].

1.2. Storage of electricity

Increasing attention is drawn by large scale grid-connected electrochemical batteries, as lithium-ion (Li-ion) battery technology [10]. The technology is well proven, has a round trip efficiency of up to 95% and it can be placed almost anywhere needed. Several studies have found this type of batteries or similar, to have an important role in a future renewable electricity supply, and that it may even be a necessity for a fully renewable electricity supply, e.g. in [11] and [12]. Others find that electricity storage is particularly important in isolated areas, such as islands suggested in [13] and [14]. However, traditional batteries have a significant cost of investment and the chemical compounds derived from the production and end-of-life disposal may have some environmental consequences [15].

1.3. Smart energy and 4th generation district heating

Other studies, using a smart energy system approach, find that large-scale grid-connected electricity storage is not feasible in general in an integrated energy system [16]. A smart energy system is a concept of the design of an energy system, that focuses on coupling of energy sectors, i.e. electricity, heating, cooling, transport and industry [17]. The argument is that other flexibility measures are more efficient and cost-effective than electricity-only storage. For example, an integration between the electricity system and district heating (DH) systems is mentioned as an important feature [18]. This enables the utilization of thermal energy storage (TES) capacities in the DH system to balance the electricity supply, e.g. with CHP or electric vapor compression heat pumps (HP).

The 4th generation of DH can be understood as the DH side of a smart energy system and has a focus on utilizing synergies in various energy infrastructures, as described in [19] and [20]. Low temperature excess heat occurs several places in the energy supply systems [21], and via low temperature DH systems and heat pumps the excess heat can be used as a source for DH production [22].

1.4. Compressed heat energy storage (CHEST)

In the CHESTER-project the so-called *Compressed Heat Energy Storage* (CHEST) concept is analyzed through modelling and simulation of the possible technological options and a prototype CHEST unit is demonstrated in the project as well. Based on the findings the technology will be developed further [23].

In the effort of the present study, an emerging technology that can work as a flexibility measure is considered – the CHEST. The technology, presented by Steinmann in [24], consists of a power-to-heat unit, a thermal storage and a heat engine driving a generator. The concept is also referred to as a *Carnot battery*, e.g. by Dumont et al. in [25] and *Pumped thermal electricity storage* by Benato and Stoppato in [26]. The CHEST technology can use electricity at times with an excess production to convert it to thermal energy which can be stored, to release the thermal energy through a heat engine to generate electricity back to the electricity grid. See an illustration in Figure 1. In that sense it is like conventional electricity storage, however, the CHEST can also work as *combined electricity and thermal storage* as indicated in the title of the present article. If a heat pump is used as the power-to-heat unit to charge the CHEST, the heat source for the heat pump can be a DH system. Similarly, the excess heat from the operation of the heat engine here assumed to be an Organic Rankine Cycle (ORC), can be fed back into the DH system. In that way heat and power is stored together and discharged together. This can potentially reach a higher total efficiency than conventional electrical storage, but a lower power-to-power ratio.

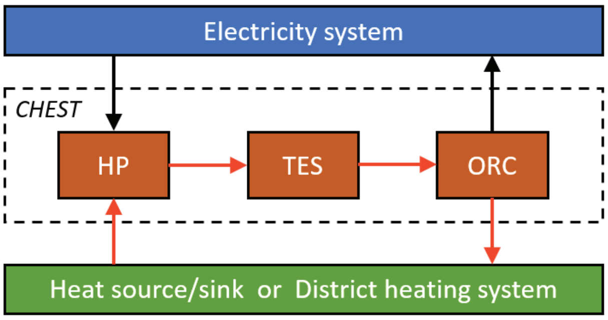

Figure 1: Conceptual illustration of system integration of CHEST with its main components; heat pump (HP), thermal energy storage (TES) and an organic rankine cycle (ORC).

The CHEST technology can be understood as a part of a smart energy system when connected to a DH system, because this will allow the utilization of synergies between the operation of the heat and electrical sides of the storage.

1.5. The Objective of the study

The objective of the analysis is to uncover the technical potential of introducing large-scale CHEST storage capacities on a national energy system level, in the perspective of the transition towards an energy supply based on sustainable resources.

A large-scale system integration of CHEST storages is analyzed in the context of the German energy system as a case. A smart energy system approach is assumed, and energy system models of Germany in a future scenario representing 2050 are used. The study includes a technical analysis of the system and the influence on the overall system dynamics by introducing a large capacity of CHEST into the supply. Two different configurations of CHEST are analyzed, with and without DH integration, and compared to Li-ion storage of the same capacity and a situation without any additional storage.

A central part of the analysis is two different scenarios for the DH supply in the 2050 situation are considered. One that represents the current supply based on mainly CHP, and an alternative where DH supply is based mainly on large-scale heat pumps.

2. National Energy System Model Development

For the analysis, a set of models is developed, where Germany in 2050 is used as a case. Two variations are derived based on alternative development pathways of DH supply.

2.1. Germany of 2050 as a case

Germany is chosen as a case for the analysis because it is a relatively large country, centrally located in Europe. In sensitivity analyses, the representativeness of this choice will be discussed. An energy system model of Germany is developed with the reference year 2050. The exact year of 2050 is not essential to this analysis, but it is to denominate a point in time where it is expected that a large share of renewable energy in the form of wind power and solar photo voltaic (PV) could be operating and the overall energy system has been electrified much further than today.

2.2. Data foundation and system assumptions

The energy system model is designed to represent the energy system of Germany in 2050, with large shares of renewable energy, a high degree of electrification and with a smart energy system approach.

The data inputs for the model of the energy system of Germany used as a starting point for the analysis are partly adapted from an existing model, developed in the framework of the IEA Technology Collaboration Programme of Energy Storage. The project Annex 28 - DESIRE focused on decentralized energy storage, and in connection to this an energy system model was developed [27]. This was based on the energy system of Germany in 2015 and designed to analyze the feasibility of different energy storage technologies and configurations. The model used in the analyses of the current study is a revised and adjusted version of the model developed in the DESIRE project. The implemented adjustments are mainly to reflect the transition towards 2050, including more renewable electricity production, reduction in fossil fuel consumption and general electrification of all sectors. A list of the key parameters adjusted in the development can be found in Table 1. Later, in Table 2, a list of a few additional adjustments related to the two scenarios for DH can be found.

The conventional electricity demand includes the electrical demands which are not assumed to change towards 2050, such as lighting, appliances, cooling and existing industrial process. The end demand of these categories may increase, but improved efficiencies are assumed to balance out this effect and therefore this demand remains the same in 2050. The capacities of onshore wind, off-shore wind and solar PV for the 2050 models are scaled proportionally based on the development trend projected in the DESIRE project [27], to a level where the excess electricity production (EEP) (see more in Section 3.2) is equivalent to 10% of the total annual electricity demand in an island mode analysis. The excess electricity is the amount of electricity, usually produced by inflexible production units, which cannot be utilized at the time of its production. The level of 10% is to keep a comparable level of fluctuating renewables in the future models. Thermal power plants are assumed to be converted towards 2050 so that 50% use natural gas and 50% use biomass.

In [28], Mathiesen and Hansen have made a study on the future energy supply in Germany, including an assessment of how the transport demand will be covered in 2050, and values for the transport sector have been adopted from this study. There is a strong focus on electrification of the transport sector, and the remaining fuel demands of petrol, diesel and jet petrol is in the current study covered with 50% fossil fuels and 50% electrofuels produced using biomass gasification, hydrogenation and synthesis to liquid fuels.

In the project Heat Roadmap Europe, which focused on the future (2050) of heat supply in Europe, it was found that heat demands in Europe should ideally be reduced by 30-50% and 40-50% of the total demand should be covered with DH [29]. In the present study, it is assumed that the overall heat demand in buildings in 2050 to be reduced by 25% of the 2015 demand. At the same time, it is assumed that the DH coverage of the total demand is increased from 15% in 2015 to 30% in 2050. These values are a bit lower than what was found in Heat Roadmap Europe because the values of that project are an expression of the ideal levels from a system perspective. The consequence of higher or lower DH demand is discussed in connection with the presentation of the results in Section 5 of the present article.

In the individual heating supply in the 2050 scenarios, the fossil fuels in the supply are replaced completely with biomass, heat pumps and electric heating in a ratio of 17.5/80.0/2.5 based on [28]. The DH supply will be described further in Section 2.3.

Table 1: Key energy system parameters defining the Germany 2050 model compared to the original model of the DESIRE project.

Parameter	Unit	Germany 2015	Germany 2050
Electricity			
Conventional electricity demand	TWh	596.3	596.3
Onshore wind	GW	41.7	201.9*
Off-shore wind	GW	3.3	108.9*
Solar PV	GW	39.6	297.0*
Nuclear power capacity	GW	8.0	0
Power plant capacity (thermal)	GW	85.6	200.0
Transport			
Petrol	TWh	220	42.8
Diesel	TWh	332	189.0
Jet petrol	TWh	100	77.8
Electricity for transport	TWh	12.1	83.7
Electrolysis for fuel production	GW	0	9.7
Biomass gasification	TWh	0	126.0
Liquid fuel production	TWh	0	162.5
Heating			
Coal, individual boilers	TWh	28.3	0
Oil, individual boilers	TWh	263.2	0
Natural gas, individual boilers	TWh	466.0	0
Biomass, individual boilers	TWh	90.8	121.0
Heat pumps, individual units	TWh_{th}	6.7	359.5
Electric heating, individual units	TWh	34.2	11.2
District heating production	TWh	159.6	234.6
Industry			
Coal	TWh	115.0	15.0
Oil	TWh	258.4	108.4
Natural gas	TWh	281.8	32.0
Biomass	TWh	39.0	39.0
Electricity (to replace fuel-based processes)	TWh	0	150.0
Hydrogen	TWh	0	200.0

*The values of wind and solar capacities are adjusted in alternative scenarios for DH supply, described in Section 2.2.

The resulting energy system is highly electrified and based on renewable sources to a much larger extent than the current system. The electricity supply, which can be seen in Figure 2, in the 2050 model is about three times the corresponding supply of 2015. At the same time, there is a substantial amount of excess electricity production in 2050, which is due to the fluctuations in the supply and the mismatch with the demands. The proportions and mix of resources are like those found in Heat Roadmap Europe for the country study of Germany [30].

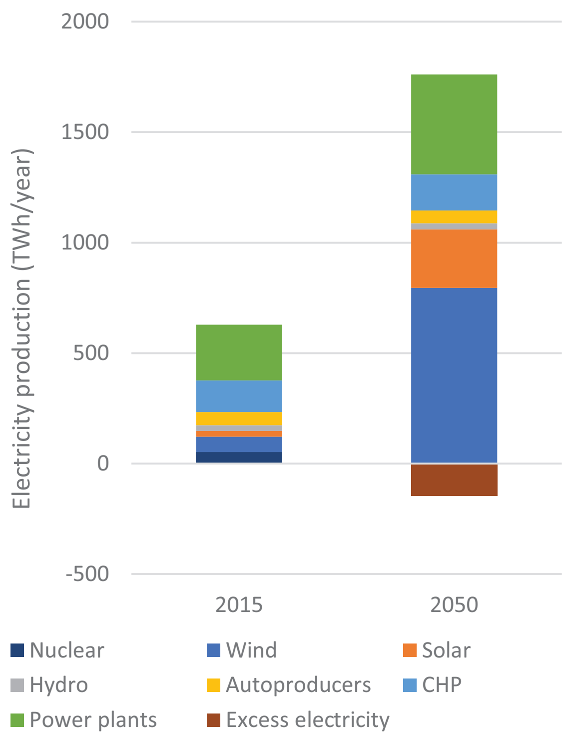

Figure 2: Electricity production divided into sources in 2015 and 2050 Fuel scenario.

2.3. Future District Heating: Two Scenarios

In the future development of energy systems, it is uncertain how DH supply will develop, particularly if the DH coverage of the total heat market will double. For this reason, two different scenarios for how the DH can develop has been analyzed; a *Fuel* scenario and an *Electric* scenario, referring to the main source of heat production. These two can be expected to show different results because of the inherent system functions of the technologies; CHP, heat pumps and CHEST. See Figure 3 and Figure 4 respectively for the two system designs. An electrified DH supply is not completely unlikely, as heat pumps for DH can already be found economically feasible today [22].

In Figure 3, showing CHEST integrated into a fuel-based system, in a situation with high RES production, the heat source for the CHEST when charging will be based on fuel boilers because the CHP will only be operated, thus producing excess heat, when RES is not covering the demand. In the case of low production of RES, the CHEST will discharge and supply electricity and replace fuel-based PP production. However, when CHEST is discharged and making excess heat available to the DH system, there is at the same time excess heat from the operation of the CHP.

In Figure 4 showing CHEST integrated in an electrified system, the CHEST is charged with electricity from renewable sources, but also with heat from renewable sources, indirectly through the power-to-heat units. In that way, no additional fuel will be consumed charging the CHEST, opposite to the CHP system. In the situation with low RES production, CHEST will be discharged and reduce the need for fuel-based production both in the electricity supply, in power plants, as well as in the heat supply, in fuel boilers. In that way the CHEST may generate an added value compared to an integration in a CHP system.

The exact parameters where the scenarios differ can be seen in Table 2. In general, coal and oil supply are replaced with biomass and gas, so the total fuel mix is two-thirds gas and one-third biomass in boilers and CHP. There is in both scenarios also a share of industrial excess heat and solar thermal heat. The excess production is larger in the 2050 scenarios due to assumed heat recovery of electrolysis and electrofuels production.

In the Fuel scenario, the supply system for DH is like the one of 2015. In the Electric scenario, the capacity of CHP plants is reduced and supplemented with a capacity of heat pumps with a capacity of 9 GW_e. With an average coefficient of performance (COP) of 3 assuming ambient heat sources, this is equivalent to a total output of 27 GW_{th}. In the electric scenario, there is a bit higher electricity consumption in the model, which reduces excess electricity production. To reach the same level of excess electricity again the capacities of renewable power production has been slightly increased.

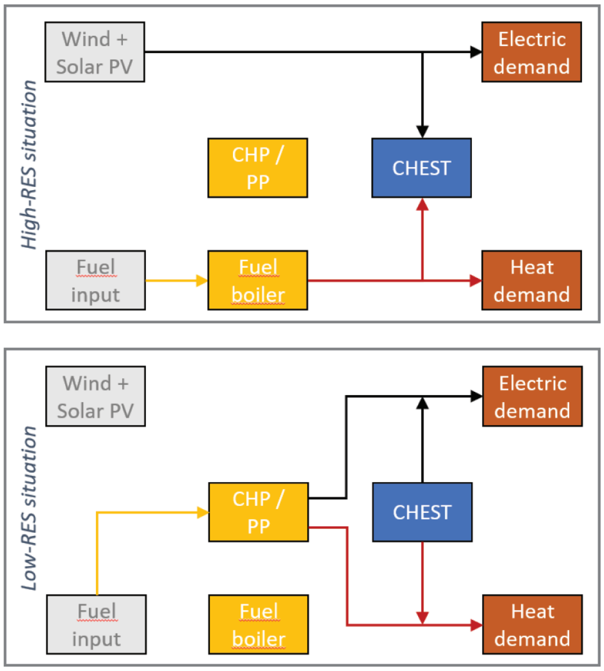

Figure 3: CHEST integrated in a CHP-based DH supply system in a situation with high production of wind and solar power (top) and one with low production (bottom).

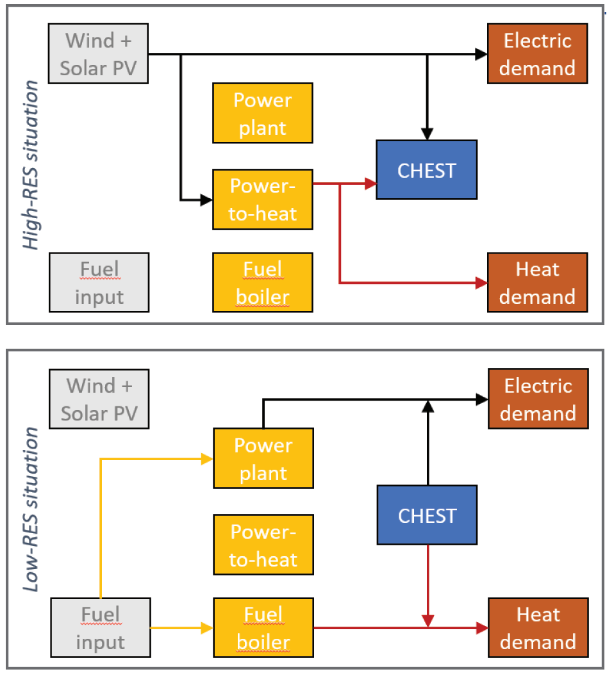

Figure 4: CHEST integrated in an electrified DH supply system in a situation with high production of wind and solar power (top) and one with low production (bottom).

Table 2: Key parameters defining the differences between the Fuel scenario and the Electric scenario.

Parameter	Unit	Germany 2015	Germany 2050 Fuel	Germany 2050 Electric
Combined heat and power	GW_e	50.1	50.1	10.0
Heat pumps	GW_e	0	0	9.0
Onshore wind	GW	41.7	201.9	208.0
Off-shore wind	GW	3.3	108.9	112.2
Solar PV	GW	39.6	297.0	306.0

In Figure 5 it can be seen how the total DH production increases from 2015 to 2050, due to the doubling of the coverage of DH to 30% of the total demand. The total production has not doubled because end-use heat savings have also been included. It can also be seen that the mix of heat sources in the 2050 Fuel scenario is like the supply in 2015. In the 2050 Electric scenario, however, electric heat pumps have taken up more than half of the total production, replacing fuel-based CHP and boiler production.

3. Model Analysis Approach

For the simulation of the models and later the impact of integrating CHEST into the models, the EnergyPLAN tool is applied, and the results will be measured in Primary energy supply, excess electricity and discharged electricity.

3.1. The EnergyPLAN simulation tool

The EnergyPLAN tool simulates the specific energy system given by the user. The energy system is modelled by providing a list of inputs in the user interface of EnergyPLAN. In this case, the energy system is the energy system of Germany. Figure 6 illustrates the basic principles of the EnergyPLAN model simulation. When the system simulation is run, EnergyPLAN seeks to meet all the energy demands (orange) using the available resources (white), storage (blue) and conversion capaci-

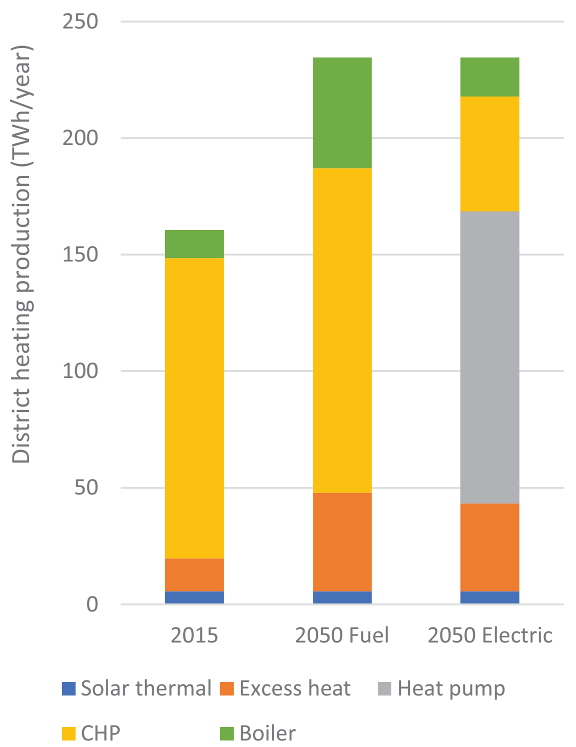

Figure 5: DH production divided on sources of heat for 2015, 2050 Fuel and 2050 Electric

ties (yellow). CHEST and Li-Ion batteries are here represented in the blue box "Electricity storage system". See full documentation of the tool in [31].

The simulation of the modelled energy system is done on an hourly basis for one full year. This enables a dynamic account of how for example electricity production from wind or solar PV is used or how peaks in energy demand or production are accommodated in the system [32]. This hourly-based approach is particularly important when modelling storages because it enables control of how storages are charged and discharged each hour when these are operated as a part of the overall energy system.

The result of a simulation is a quantitative description of how the system operates under the given assumptions and conditions. This can be generated as annual, monthly, or hourly values for a range of different parameters including energy system flows, primary energy supply, cost components, fuel distribution and more.

3.2. Key resulting indicators

Three indicators are used to compare the simulation results. EnergyPLAN is commonly used in analyses comparing several parameters in the same study [33].

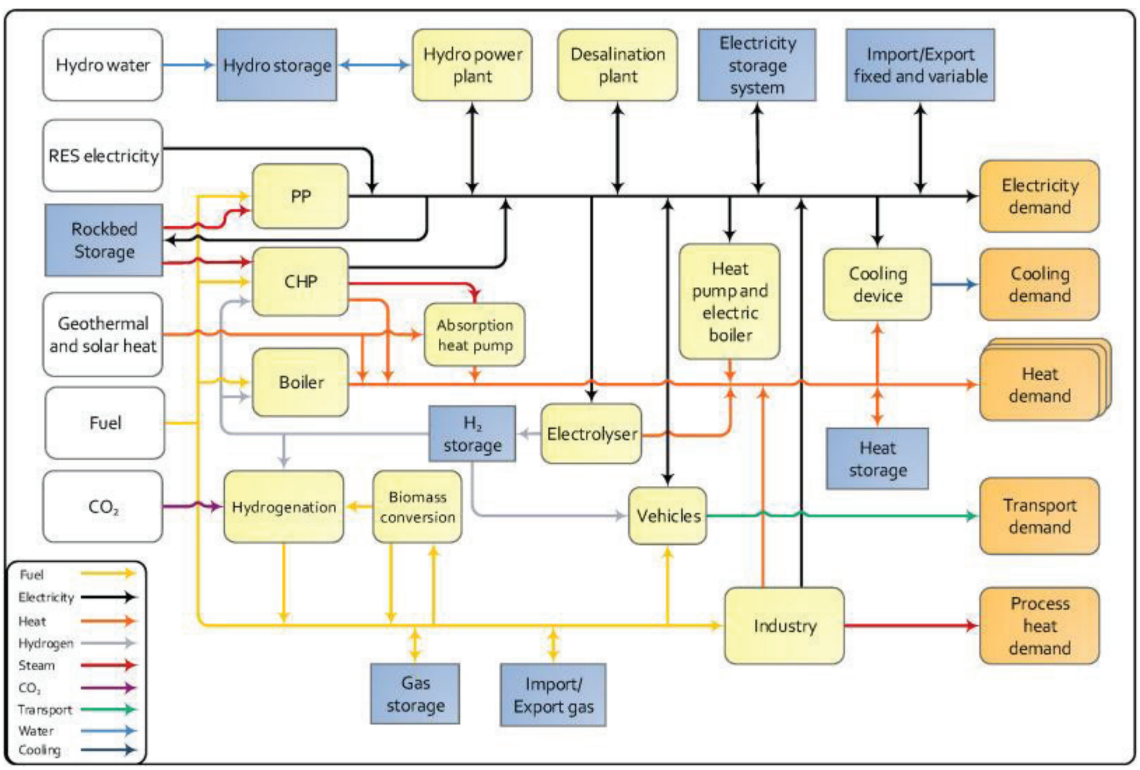

Figure 6: Overview of resources (white), conversion (yellow), storage (blue), supply infrastructure (arrows) and demands (orange) included in EnergyPLAN *[32]*.

In the following the three main indicators for the comparison of results are presented:

The *primary energy supply* (PES), is a sum of all resources used in the energy system through one year to supply the energy demands. It includes fluctuating renewable sources, such as wind and solar energy, as well as fossil and low-carbon fuel-based energy, such as oil, natural gas and biomass. This value indicates how effective the energy system is to cover the demands in comparison to other alternatives.

The *excess electricity production* (EEP), is the amount of electricity that cannot be used in the energy system at the time of production. In some cases, the electricity can be exported, but in other cases, there is no possibility to export and then it will require curtailment of production. In energy systems with a large share of inflexible electricity production, such as wind power or nuclear, there will be almost always some EEP. This is a good analytical indicator of how well a certain measure, e.g. storage, can increase the flexibility of the electricity system and thereby the ability to accommodate more renewable electricity.

Discharged electricity, is the amount of electricity that can be fed into the power grid, after a period of storage. If the loss from the storage is high, the discharged electricity can be significantly lower than the electricity charged into the storage. In this way, the discharged electricity can indicate the utilization rate of the storage as well as the efficiency of the storage use.

3.3. Parameters and assumptions for sensitivity analyses

In the following the assumptions for the sensitivity analyses are listed:

- *a.* *Wind to PV:* 1/3 of the annual electricity production from wind power is replaced with a capacity of PV producing a corresponding amount of electricity.
- *b.* *PV to hydro:* 1/3 of the annual electricity production from solar PV is replaced with a capacity of hydro power producing a corresponding amount of electricity.
- *c.* *Flexible demand*: 25% of the conventional electricity demand can be flexible if needed, meaning that it can be moved within one day.
- *d.* *Smart charge EVs*: 25% of the electric vehicles are allowed to charge using a smart charging scheme.
- *e.* *Electric boiler*: 10% of peak DH demand, equivalent to 6.3 GW of electric boiler capacity in total is installed in the national DH supply.
- *f.* *CHEST efficiency*: The electric output efficiency of the CHEST ORC is reduced from 15% to 12%.
- *g.* *Existing batteries*: 1 GW of electrical storage, identical to the Li-ion storage presented in Table 3, is introduced before implementing the analyzed configurations.

4. Energy Storage Assumptions

The analysis of CHEST is based on characteristics for the technology found in the CHESTER project ([34], [35] and [36]). Two different ways of implementing CHEST is investigated; one where CHEST uses a free heat source, and one where CHEST is integrated with a DH system. The CHEST storage is compared to an alternative of a Lithium-ion (Li-ion) battery.

4.1. Technical assumptions

In the modelling of scenarios with CHEST integrated a few technical assumptions have been made to represent its characteristics. Table 3 presents the key technical assumptions for CHEST and the used alternative in Li-ion. The charge, discharge and energy storage capacity of CHEST and Li-ion batteries are assumed to be the same when compared.

The assumed COP of 4.0 in the CHEST heat pump for charging the thermal storage means that one unit of electricity is consumed for every three units of heat from the heat source. This means that 25% of the energy input is from electricity and the remaining 75% is from heat sources. In the discharge of the storage, 15% of the energy content is delivered as electricity and 85% remains as heat. In the scenarios with district heating exchange, it is assumed that all the remaining heat can be recovered, even though it may be difficult to reach in practice. However, the exergy level is reduced through the storage, as the amount of electricity produced by the ORC is lower than what consumed by the heat pump. A sensitivity analysis covers a drop in the ORC efficiency. There will also be a heat loss connected to the storage of heat, piping etc. but it is not a large share of the total and it is disregarded in this analysis.

These assumptions are based on a heat source of 65 °C and a heat sink of 35 °C, corresponding to a relatively low temperature level of DH systems. The thermal temperature storage level is assumed to be 160 °C. If the heat source temperature is higher, the COP of the CHEST-heat pump could be higher when charging the storage, but that would also reduce the efficiency of the heat recovery of the ORC in the district heating scenarios.

The capacity of 1 GW is set due to the limitation in the DH demand. With this dimensioning, the district heating output recovered from the ORC is about 60% of the average summer district heating demand. If the dimension gets bigger than this, the benefit of the heat integration will decrease.

Regarding the Li-ion battery, the assumed round trip efficiency is 95%. The charging, discharging and energy storage capacities are assumed to be the same as for the CHEST, where thermal storage capacity for the CHEST was converted to an equivalent electric capacity of the electric battery.

Table 3: Technical assumptions for CHEST and Li-ion energy storage.

Parameter	Unit	Value
Charge and discharge capacity (CHEST and Li-ion)	MW_e	1,000
Energy storage capacity (CHEST and Li-ion)	GWh_e	50
CHEST Electrical efficiency of heat pump (COP)	-	4.0
CHEST Electrical efficiency of ORC	-	0.15
CHEST Thermal recovery efficiency of ORC	-	0.85
Li-ion round-trip efficiency	-	0.95

4.2. System integration and operation strategy

Two different strategies of system integration are assessed. They represent the relevant integration in two different situations:

1) Where DH is not present or relevant for CHEST integration
2) Where DH is present and available for CHEST integration

These are discussed and elaborated in the following sections 4.2.1 and 4.2.2.

4.2.1. Free eeat – Electricity only

This implementation strategy is to use the CHEST as electricity storage only. It assumes that the CHEST is in a place with an available excess heat source. The heat source is assumed to be an excess product of another activity, for example, an industry, where all the heat would otherwise be dissipated into the environment, and thereby do not result in additional fuel consumption when utilized by a CHEST system. The heat source is also assumed always to be available and at enough quantity and temperature level. In this case, the operation of CHEST will have a free heat source for the heat pump, but there will also not be a revenue of the heat production of the ORC because there already is an excess of free heat at the location, so the heat will be dissipated. Hence, the CHEST will only be exchanging electricity in this setup, and the operation strategy will be to only optimize against the electricity system.

4.2.2. Electricity and district heating exchange

This implementation strategy is to use the CHEST as electricity storage but with an exchange of heat with a DH system. In this strategy, it is assumed that heat for the heat pump of CHEST will be drawn from the DH system and that the heat production from the ORC will be injected back into the DH system. This means that there will be an additional heat demand in the DH system associated with the charge of the CHEST, but also a potential reduction in the need for heat production when CHEST supplies heat back into the DH system. The additional consumption and potential reductions will depend on the time of the operation of CHEST because the marginal production unit in the DH system changes from hour to hour, and they have different energy consumption profiles associated with them.

In this case, the operation strategy of CHEST is mainly to work to balance the electricity system, and the exchange of heat will be a secondary product of the operation. This is seen as a reasonable assumption because short-term balancing of the electricity system is typically more challenging than in DH systems, and it is not expected that price margins in DH production will be enough to charge the CHEST at high electricity prices or discharge at low electricity prices in many hours during a year. Even though CHEST is operated with a focus on the electricity system, the excess heat may be feasible to utilize in DH, possible with a thermal storage connected to it.

5. Results and Discussion

In this section, the results of the analysis are presented. First, the main results are presented, followed by several sensitivity analyses of the key results.

5.1. Results of energy system analysis

The results of the analyses of the 2050 scenarios are shown in Figure 7. The results for the two scenarios for the German energy system, 2050 Fuel and 2050 Electric can be seen for the three storage configurations.

The configurations Li-ion and CHEST El-only perform almost identically respectively in 2050 Fuel and 2050 Electric. This means that they are not affected significantly by the way DH is supplied. It makes sense as they are not directly integrated with DH. It can also be seen that in both cases CHEST El-only consumes the same amount of excess electricity as for the Li-ion configuration (~1.7 TWh), but at the same time the CHEST El-only configuration results in a lower reduction (~2.4 TWh) in PES than the Li-ion (~3.7 TWh), caused by the lower power to power ratio. This means that from a technical energy system perspective, CHEST El-only is less attractive than a Li-ion battery in this sense. If CHEST can come with a lower investment and/or operation cost compared to the Li-ion battery, it might be economically competitive, however, thatis is not analyzed here.

When it comes to the results for the CHEST DH-exchange configuration, the conclusions are different. The amount of electricity charged into the storage and the electricity discharged and supplied into the electricity grid remains the same as in the CHEST El-only configuration. The change in EEP is the same in the 2050 Fuel scenario (~-1.7 TWh), whereas in the 2050 Electric, it is significantly higher (~-3.1 TWh). This indicates that the CHEST implementation enables the system to utilize more EEP than in other cases. The reduction in PES shows a large difference between the scenarios for the CHEST DH-Exchange configuration.

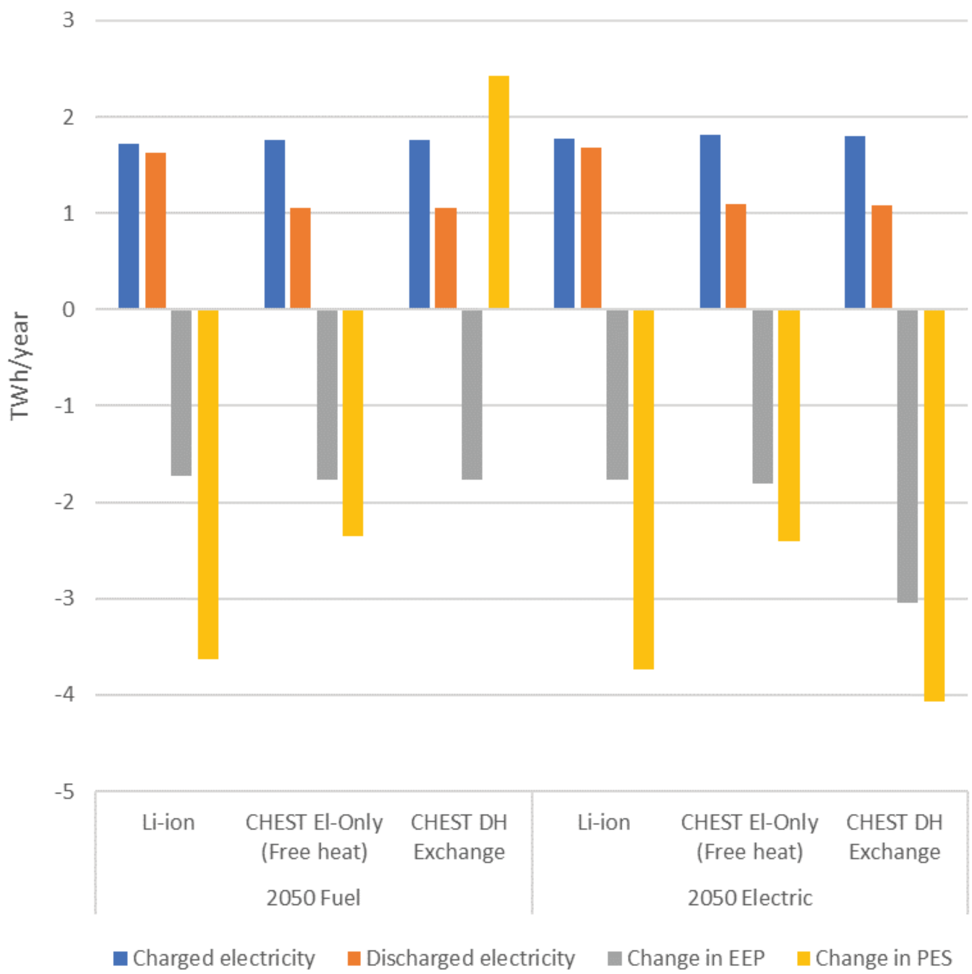

Figure 7: Main results of the three storage configurations in the Fuel-scenario and the Electric scenario. Results expressed as the change from the reference model without storage.

In the CHEST El-only configuration, the reduction is negative (~-2.4 TWh), which means that the system has a larger primary energy supply than without the storage. This indicates a mismatch between the electricity side and the heat side of the storage operation in terms of the energy system dynamics and balancing. The reason will be discussed further below. On the other hand, in the 2050 Electric scenario, the reduction in PES is positive (~4.1 TWh), and it is even larger than the resulting reduction in PES in the Li-ion configuration.

In Table 4 the changes in the energy supply caused by the implementation of the CHEST storage configurations can be seen. The El-only configurations in both scenarios only result in changes to the electricity supply, whereas the DH-exchange configuration results in changes in both electricity and DH supply.

In the 2050 Fuel scenario, the El-only configuration has a positive impact as EEP is utilized to replace thermal power plant (PP) production. The negative contribution from CHEST (0.7 TWh) is the loss in the power to power conversion, which to some extent is recovered when implemented into DH. Only to some extent, because the DH-exchange configurations also generate a surplus heat.

In the DH-exchange configuration of the 2050 Fuel scenario, CHP production is replaced (-6.2 TWh) but PP production increased (5.2 TWh). As the CHP plants have a better system efficiency than PPs, this is not an effective shift. In the DH balance, the heat production from the CHP plants at the same time is replaced (-5.3 TWh) with fuel boilers (5.2 TWh). This means that there is almost no saving in fuel in the electricity supply and an increase in fuel consumption for the DH supply. This is the reason for the result seen in Figure 7, that the introduction of the CHEST El-only configuration in the 2050 Fuel scenario causes an increase in PES.

In the 2050 Electric scenario, EEP is utilized to replace CHP production (-2.1 TWh) but without an increase in PP production. In the DH supply, the corresponding reduction in heat production from CHP (-1.8 TWh) is replaced with heat pumps (0.6 TWh) using electricity instead of fuel, and fuel boilers (1.0 TWh). This means that fuel-consuming production has been replaced in the electricity supply, and in the DH supply, the CHP production is only partly replaced with fuel boilers. This is the reason for the large positive effect of the CHEST DH-exchange in the 2050 Electric seen in Figure 7.

Table 4: Resulting changes in the energy supply for electricity and DH when implementing the two CHEST storage configurations in each of the 2050-scenarios.

		2050 Fuel		2050 Electric	
(TWh/year)		El-only	DH-ex	El-only	DH-ex
Electricity supply	CHP	0	-6,2	0	-2,1
	PP	-1,1	5,2	-1,1	0
	EEP	-1,8	-1,8	-1,8	-3,0
	CHEST	-0,7	-0,7	-0,7	-0,7
District heating supply	Heat pump	0	0	0	0,6
	CHP	0	-5,3	0	-1,8
	Fuel boiler	0	5,2	0	1,0
	Surplus heat	0	-0,6	0	-0,5
	CHEST	0	0,7	0	0,7

These results point in the same direction as the theoretical discussion presented in 2.3, than a CHEST system might not be feasible in the current DH supply, however, in a future electrified supply, the combined electricity and heat storage might be beneficial.

5.2. Sensitivity analysis results

In Figure 8 the main results of the sensitivity analyses can be seen. The assumptions for these can be found in Section 3.3. The figure shows the reduction in primary energy supply after the implementation of the storage configuration. The positive result of the CHEST DH-exchange in the 2050 Electric scenario, is assessed for its sensitivity to some uncertain parameters and system assumptions. The first two columns in the figure are identical to the ones of Figure 7 for Reduction in PES for Li-ion and CHEST DH-exchange respectively in the 2050 Electric scenario.

For the “Wind to PV” and “PV to Hydro” columns the tendencies are like the ones of the reference as the CHEST alternative remains with the highest reduction in PES. The overall level of the savings, however, is affected in both cases. When the wind-based electricity production is replaced with a corresponding amount of electricity production from PV, the potential increases due to the hourly distribution of the two sources over the year. A change towards PV creates more EEP, and therefore a larger potential for electricity storage. Similarly, a change from PV towards hydro reduces the EEP, and thus the potential for electricity storage in general. This indicates that the feasibility of CHEST, and electricity storage in general, is dependent on the regional location and its dominating resources.

For the “Flexible demand” and “Smart transport” the changes from the reference are relatively small, but the introduction of flexible demand reduces the potential slightly. The introduction of “Existing batteries” in the system before implementing CHEST, can also be a competing flexibility measure, which has a slightly negative influence on the savings because it reduces the EEP and hence the foundation for additional electricity storage. This indicates that the feasibility of CHEST is only moderately sensitive to the presence of other flexibility measures. Of course, it will also be a matter of how far alternative flexibility measures will be able to be upscaled.

The “Elec. Boiler” shows that introduction of electric boilers in DH will result in a larger reduction of PES for CHEST, even though it will also reduce the EEP. This means that a further electrification of a DH system in which CHEST is integrated, will increase the potential benefit of CHEST.

When looking at the CHEST efficiency, if CHEST achieves a lower efficiency than assumed in the main analysis, from 15% to 12% electric efficiency output of the ORC, the reduction of PES is no longer larger than the Li-ion battery alternative. This show that the results are sensitive to the efficiency. A lower efficiency will make the competition with Li-ion batteries and other flexibility measures harder but not necessarily mean that the technology does not have a role to play.

6. Future Perspectives for CHEST Technology

The results indicate that CHEST can hardly compete with conventional electricity storage in the short term. Both because CHEST is at an early development stage compared to e.g. Li-ion batteries, and capital costs are still significantly higher [36]. At the same time, the present results show that CHEST is not effective in the integration with CHP-based DH, which covers most of the current DH [37]. In the longer-term future, however, costs of the CHEST components may have decreased with the commercialization of the technology. The costs will have to be reduced significantly because at the current levels the CHEST system is far from being directly economically competitive [36]. At the same time, the current political development in the EU indicates that DH systems might be developed more broadly in Europe [38], as well as electrification of the supply.

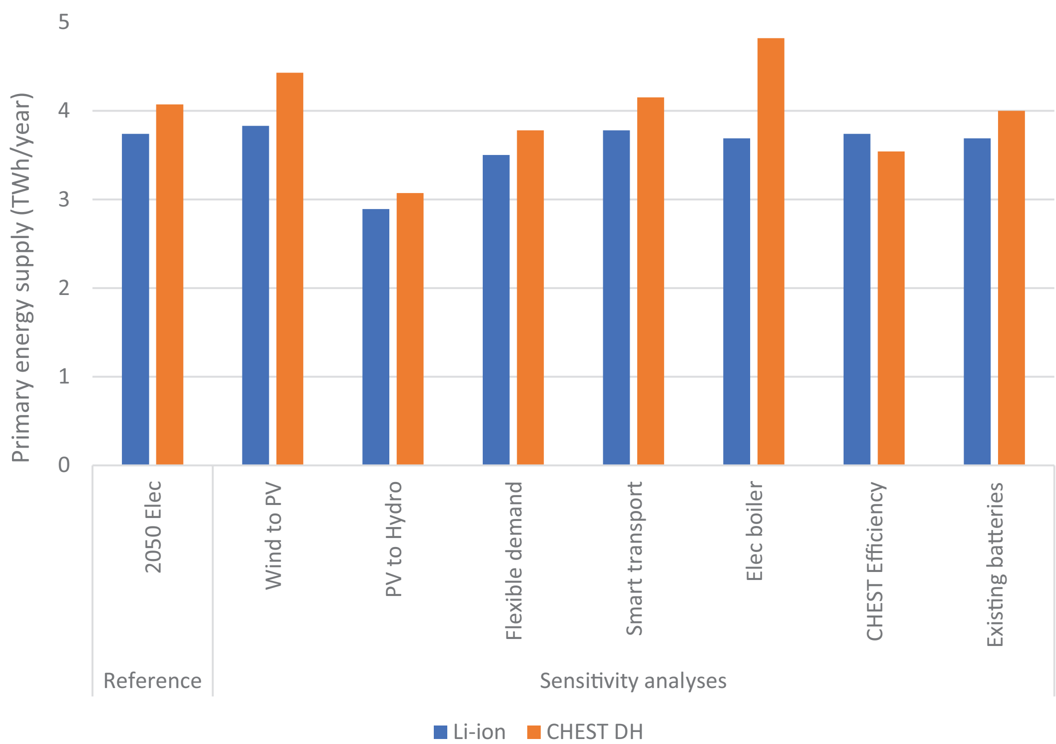

Figure 8: Results of sensitivity analyses to the 2050-Electric scenario for Li-ion and CHEST DH-Exchange

From an environmental point of view, there might be some benefits of using CHEST compared to conventional batteries [15]. CHEST is not necessarily free from chemicals, but there are many options in the choice between e.g. refrigerants or thermal storage medium, which can be included in the assessment.

The analyzed scenarios for 2050 is highly electrified, but assumes an increased share of biomass consumption, even though the sustainability of biomass consumption for energy purposes is controversial [39]. On the long term, the biomass consumption may be reduced with increased electrified demand and production of electrofuels and other hydrogen-based supply, but it is uncertain when the current development towards more biomass consumption for energy purposes will change. Further electrification with a larger production of fluctuating renewable electricity can be expected to increase the potential for electricity storage and CHEST systems.

7. Conclusions and Future Works

The study has investigated the technical energy system potential of CHEST technology in a national energy system context. Through the analyses, Germany has been used as a case, where a possible energy system of 2050 has been developed for the country. Two scenarios, with different DH supply, have been analyzed, comparing two different configurations of CHEST with Li-ion battery storage.

The results show that if CHEST is integrated as electricity-only storage, it can reduce PES, however not as much as the Li-ion alternative. If CHEST is integrated with a DH system, mainly supplied with CHP plants, the CHEST cannot effectively reduce PES due to the operation dynamics of CHP units and CHEST. However, if the DH system is supplied mainly using heat pumps, the system can reduce PES by 4.1 TWh/year compared to 3.7 TWh/year in the corresponding Li-ion alternative. This indicates that if the DH supply is electrified using large-scale heat pumps, CHEST might be a better alternative from a technical energy system perspective than conventional electricity storage, such as Li-ion.

A sensitivity analysis shows that the CHEST system is sensitive to the assumed electrical output efficiency of 15%, where a reduction to 12% efficiency reduces the benefit of the CHEST to a lower level than the Li-ion case. On the other hand, it was also found that introducing electrical boilers in the DH supply will increase the potential for CHEST.

Based on the analysis CHEST is considered a potential competitor to conventional electric storage, in places with DH based on electrified sources, if the investment costs can be significantly reduced from the current short-term expectation of the development of the costs. There are several issues that could reveal a larger potential for CHEST integration in DH systems, including an optimization strategy of the system operation in the electricity and DH markets. It might also be possible to reduce the system costs further if the system could be more directly integrated with an existing DH plant with heat pumps and electric boilers on site.

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