CHESTER

Compressed Heat Energy
Storage for Energy
from Renewable sources

D6.4 Market technological potential

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Glossary, Abbreviations and Acronyms

CEEP	Critical excess electricity production
CHEST	Compressed Heat Energy Storage
DH	District heating
EEP	Excess electricity production
EES	Electric energy storage
HP	Heat pump
HT	High temperature
HT-TES	High temperature thermal energy storage
LHV	Lower Heating Value
LT	Low temperature
O&M	Operation and maintenance
ORC	Organic Rankine Cycle
P2P	Power-to-power
PES	Primary Energy Supply
PV	Photovoltaic
PtX	Power-to-X
TRNSYS	Transient System Simulation (software)
TSO	Transmission System Operator

Executive summary

This report is the first of two reports on market analysis and replicability potential of the market potential for compressed heat energy storage (CHEST). The first with a focus on the technical market potential and the second will elaborate on the economic market.

CHEST technology in brief

A CHEST is a proposed novel technology for electricity storage, where the electricity is storage in the form of thermal energy. A CHEST consists of three main componenents;

1) a high temperature heat pump to convert electricity to the form of heat
2) a thermal storage to store the heat generated from the heat pump
3) an organic rankine cycle (ORC) unit to convert the stored heat back into electricity

This allows storing when there is excess production from renewable sources, and production of electricity when there is lower production or high demands. A CHEST potentially has a range of technical advantages and possible configurations. These include high energy efficieny, many possible material combination, site-independent installation, possible integration in industrial systems or for district heating and cooling.

Analytical approach

The study is conducted in two parts; 1) an initial screening of the long-term technical capacity potential for CHEST in selected countries and 2) a detailed technical analysis and evaluation of the potential energy system effect of the introduction of CHEST in one case country.

The screening of the capacity potential aims to identify the scale of the technical market in which CHEST may be feasible. This is done usign energy system models of the six EU member states that is represented in the CHESTER consortium; Germany, Italy, Spain, Belgium, the Netherlands and Denmark for the year of 2050, where large renewable energy penetration is present. The screening assesses the long-term maximum technical potential, in terms of installed capacity, in an electricity-only integration as well as in a district heating integration of CHEST. The assessment relates to specific energy system characteristics of the countrie’s energy system models, and is based on simulations in the modelling and similation tool EnergyPLAN.

The second part of this study presents a detailed analysis of the technical market potential for CHEST, using the case of Germany, as it represents well the EU average. The technical market potential refers to the fundamental imbalances between supply and demand and the possible savings in energy consumption induced by introduction of storage. This includes the energy mix according to the projection for 2020 and 2050 which were specifically developed for the purpose of this study. The energy system models include all main energy demand categories, heat, electricity and mobility to be able to capture cross-sector impacts of CHEST. The models are designed for and analyzed in the energy system simulation tool EnergyPLAN. The 2020 model represents the energy system of today, while the 2050 model represents a possible scenario of how the energy system in Germany will look in 2050. The 2050 model is based on the 2020 model as a starting point, but with a substantial reduction of fossil fuels, increase of renewable energy supply and general electrification of the energy supply.

In addition to the 2050 model, two scenarios are suggested on how the district heating supply could develop in the future. One alternative is a supply similar to the current supply, mainly based on combined heat and power (CHP) and a second scenario where district heating is mainly based on heat pump using low-grade heat sources. The CHEST is implemented in different ways in both scenarios, to reflect suitable application of the CHEST technology to the envisaged market . One is a situation where CHEST works as electricity-only storage, where the heat source come as en excess source from the industry and heat output when discharging is dissipated into the environment. A Li-ion storage of the same capacity as the analyzed CHEST is included as a point of comparison as one of the main competitors in the market, even though this study is not an actual analysis of the competitive relation between the technologies, which would need the economic aspects included.

Results and discussion

The results of the screening of the technical market potential in the two different ways of implementing CHEST, in terms of installed capacity, can be seen in Figure A. It can be seen that the scale for the potenital of the electricity-only storage integration is many-fold larger than the potential allowed by the district heating integration. This is due the the electricity demands being larger than the district heating demands in general, but also that there is a larger energy flow on the heat side of CHEST. E.g. 1 MWh electricity produced by the ORC, but approximately 5 MWh heat produced at the same time.

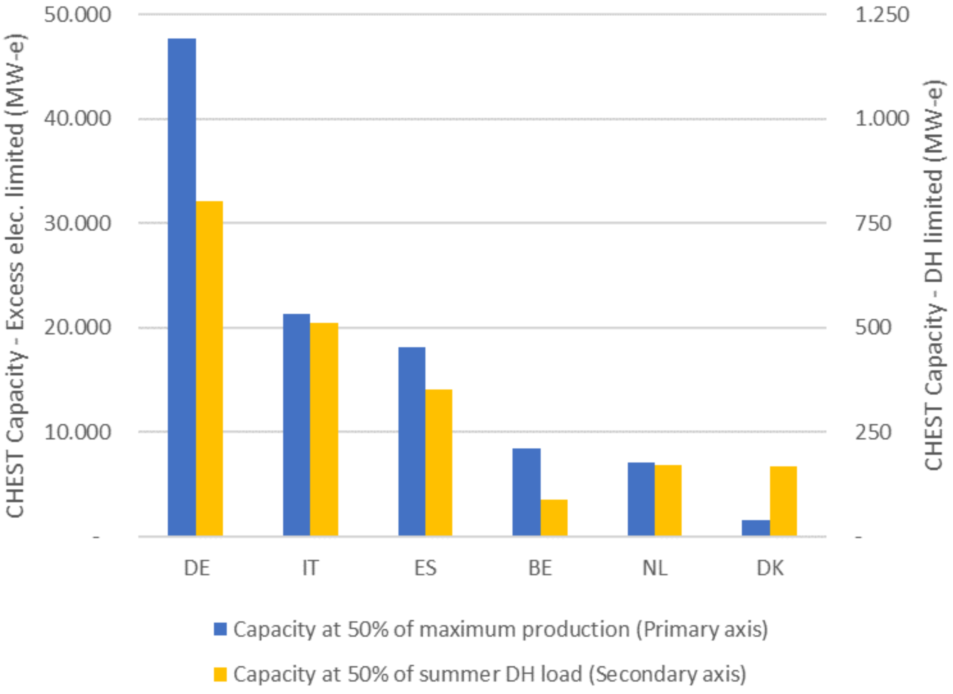

Figure A: Main technical results of the capacity screening for the selected countries in 2050 and the two diffent ways of implementing CHEST.

The results of the second part of the study show that the technical potential for CHEST in 2020 is very low because there is only little excess production of electricity. With an increase of renewable electricity penetration in the short-term future, the technical potential for storage may increase. However, the potential for CHEST, in terms of reduction in primary energy supply varies and is lower than for the Li-ion battery in the electricity-only configuration, and higher in primary energy when integrated with district heating.

In 2050, there is a potential for electricity storage in terms of reduction in primary energy supply due to a higher share of fluctuating renewables and hence larger excess electricity production.

This can be seen in Figure B. There is a potential reduction of primary energy supply in the electricity-only configurations of CHEST in both scenarios (with and without district heating integration), however, the potential is lower than the corresponding result for Li-ion storage. For the CHEST configurations with district heating integration, there is a difference in the results between the two scenarios of DH supply. In the fuel-based scenario, there is an increase in the primary energy supply which indicate that CHEST is not very suitable in integration with CHP based district heating. On the other hand, in the electric scenario, the potential for CHEST in terms of reduction of primary energy supply is the highest, even in comparison with the corresponding Li-ion storage configuration.

The main results of the sensitivity analysis is, that introduction of further electrification of district heating through electric boilers will increase the potential of the CHEST system. However, a reduction of the electric output efficiency of the CHEST will reduce its potential to a lower level than the Li-ion storage but not eliminate it.

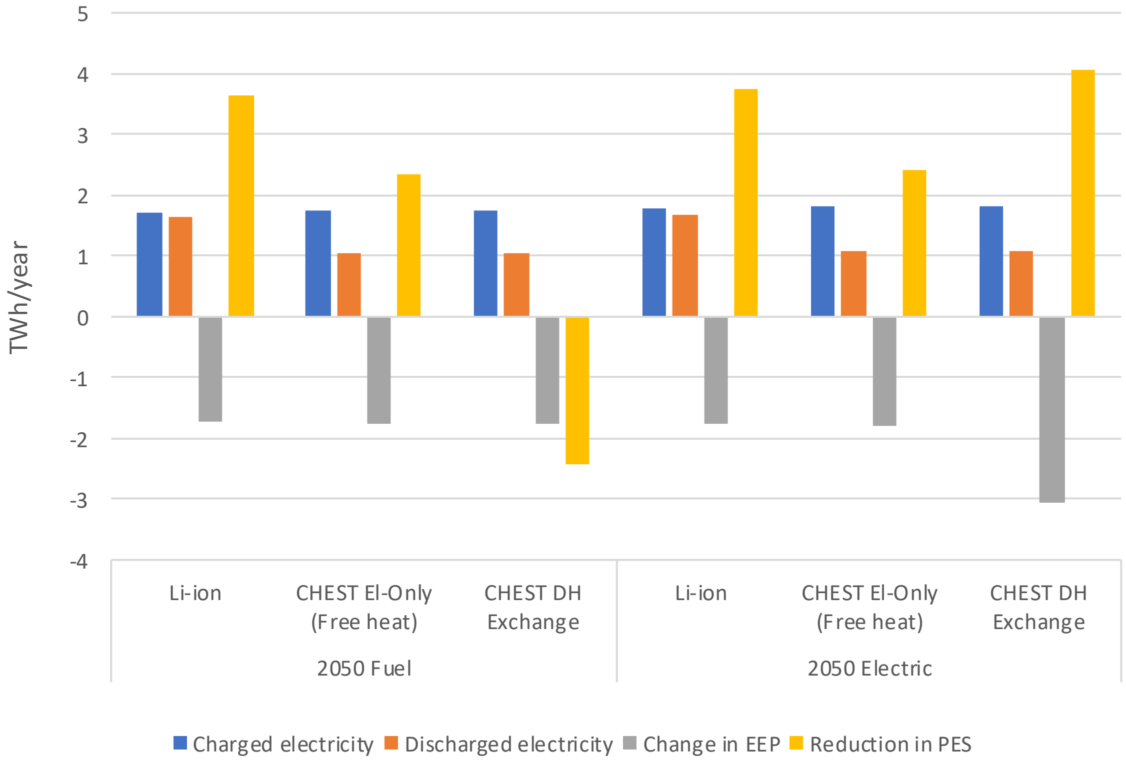

Figure B: Main technical results of the two 2050-scenarios for the relevant storage configurations, Li-ion, CHEST El-only and CHEST DH-Exchange

The appendix to the report contains a separate assessment of the specific business case with the CHEST system operating according to arbitrage on the spot andbalancing electricity market according to the future electricity price prognosis in 2040. The higher level and fluctuation of the electricity prices in 2040 increase the operation times of the HP and the ORC compared with the existing market prices. This is due to a higher demand for charging and discharging which eventually increases the annual profit. This specific business case which accounts for the upfront cost into the technology do not reach a payback of the investment.

Conclusions and future work

It can be concluded that there is a technical potential for the CHEST in integration with electrified district heating system in future renewable energy systems but with current CHP-based DH there is very little or no potential (Scenarios 2050 Fuel, CHEST El-Only and CHEST DH Exchange in Figure B, respectively). In cases without DH integration (Scenarios CHEST El-Only in Figure B, both, 2050 Fuel and 2050 Electric) there is a technical potential but it is lower than for integration with electrified DH and also lower than the Li-ion alternative.

Generally, two different conclusions on the technical potential potential for CHEST can be drawn. First it is found that the technical market potential for electricity storage and hence, electricity-only operation of CHEST, in terms of installed capacity, is significantly larger than the potential for district heating integrated CHEST storages. However, the opposite trend is found in the detailed analysis of the energy system impact of installing CHEST, where the larges technical potential seems to be in the district heating integrated systems.

It should be noticed that the technical potential is not necessarily corresponding to economic potential, though, it indicates where it is more likely to find an economic potential. The economic potential will be assessed in more detail in the future publication of the CHESTER project named *Market replicability potential*.

1. Introduction

1.1. Purpose and Scope

The purpose of the study presented is to contribute to an assessment of the market potential for CHEST, to enable a more focused planning and work on the technology and future marketing of it.

There are two general aims of the current work documented in this report. Firstly, the technical market potential found for CHEST in this study, can in itself indicate to which extent it may be feasible to implement CHEST systems, if the economy allows for it. Secondly, the work documented in this report will work as the foundation for the analyses of the economic analysis that will be conducted in the second phase of the work documented in this report, which will be documented in the second report named *Market replicability potential*.

1.2. General market situation for CHEST

A number of publications under the CHESTER project have dealt with the market situation for CHEST, including potential customers, competitors, regulatory framework, barriers for market introduction and business cases. These aspects are not analysed further in this report, but the analysis builds on and elaborates these findings. In the following a few central points from these are presented and summarized.

1.2.1. Customers and competitors

Important aspects of the market situation are the potential customers or buyers of a CHEST system as well as the possible competitors. This has been covered in the CHESTER publication *Detailed PESTEL and PORTER analysis of the CHEST system* [1]. Of possible customers can be mentioned:

- Power plants (conventional and renewable)
- Industries
- Distribution system operators (DSO’s)
- Transmission system operators (TSO’s)
- District heating companies
- Other entities or utilities operating within the electricity market

The competition in the market can be seen as a combination of direct competitors as well as other products or services that can work as substitutes [1]. The following competitors or substitutes can be mentioned:

- Electrochemical storage (e.g. Li-ion batteries)
- Mechanical energy storage (pumped hydro, compressed air, flywheel)
- Electricity interconnection between countries and regions
- Demand side management and flexible demand (e.g. smart charging of electric vehicles)
- Sector coupling solutions (e.g. power-to-heat and thermal storage)
- Hydrogen production and conversion to either electrofuels or back to electricity

The CHEST storage is expected to decrease its investment costs in the future if the technology is developed further and gets a market share. However, several of the competitors can also be expected to reduce in investments costs.

1.2.2. Framework conditions and market trends

In the CHESTER publication *Business cases definition and baseline for business models* [1], different cases have been analysed to identify issues in the market implementation under different framework conditions. As a general conclusion of this work, it is observed that the current electric market conditions are not very favorable for this type of market actors, i.e. electric energy storage actors. The current regulation is still based on an old way of seeing the electric grid, i.e. with few and dispatchable producers of electricity and many consumers. However, given the increasingly larger share of renewable energy sources (in good part non-dispatchable) in the electricity production mix, the fluctuation in the electricity production and electricity prices will increase. Currently, most of the regulation of the electricity grid is provided by fossil fuel-fired plants. However, if these are to be phased out, either for stricter environmental regulations or for increased taxation on fossil fuels and/or CO2 emissions, electric storage technology will become essential to still guarantee the cover of the demand, and a more economically favorable framework will need to be posed. Indeed, the Renewable Energy Directive (Directive (EU) 2019/944) obliges Member States to open their power grids to energy from renewable sources and to even give them priority, and this will definitely contribute to the change. Additionally, the regulation on electricity storage is likely to change. Electric energy storage is now the in the agenda of policy makers in different countries.

In a number of more specific barriers to the growth of CHEST and electricity storage in general have been identified in [3]. The barriers listed are:

- Lack of familiarity with EES among utilities, regulators and financiers
- High upfront costs. Although the cost composition changes from one EES technology to another, all of them are characterized by high investment costs and relatively low operation costs
- Need for skilled and experienced technicians to maintain and operate the systems
- Regulations preventing third-party or customer ownership of certain distributed energy resources
- Regulations preventing EES from competing in energy, ancillary service or capacity markets

1.2.3. Economic feasibility assessment

The economic aspects are not included in the present analyses, however they will be elaborated in the extended version of the analysis which will be documented in the abovementioned report.

In Appendix 1 of the present report, an analysis is summarized of a concrete case study of Aalborg in Denmark, where the CHEST is simulated for a specific location and set of conditions. The simulation is done for 2016-electricity prices for Denmark as well as prices delivered from the Danish national TSO, Energinet for the year of 2040. The study also includes specific operation costs for the different units and consideration about the potential electricity markets.

The results show that there is a substantially larger revenue of CHEST operation using the projected 2040 electricity prices than the 2016 data. This mirrors well the results of the technical study presented in this report, where 2020 shows a small potential but 2050 a much larger potential.

The case study presented in Appendix 1, however also finds that currently known and expected prices for components and total investment costs for the CHEST system are far too high for it to be economically feasible when including the capital costs, even using the 2040 electricity price assumptions.

This points to the importance of looking closely at the power-to-power ratio, investment costs and potentially other benefits or sources of income for the CHEST system when conducting the economic analyses in the upcoming work.

1.3. Content and structure of the document

In this report, an analysis of the technical market potential for CHEST is conducted. It includes a combined analysis, consisting of a screening of the capacity potential, followed by an analysis of the energy system in Germany as a case, and models representing 2020 and 2050 are developed. The choice of Germany will be discussed further in Section 2.5. With these models it is analyzed how a CHEST storage will operate during one year, using different storage configurations. In addition, two scenarios of how the future district heating will be supplied are analysed for the difference in potential for CHEST; one where district heating is mainly covered with combined heat and power (CHP) and a second one where the DH supply is mainly covered using heat pumps.

The document contains in Chapter 2 a presentation of the energy system models, data sources and analytical approach. In Chapter 3 the results of the different parts of the analysis are presented and discussed, including sensitivity analyses. In chapter 4 the main conclusions are listed and in Chapter 5, the references for the work are listed.

Chapter 6 is an appendix and contains a separate assessment of the CHEST system operating according to arbitrage on the spot and regulation electricity market according to the future electricity price prognosis in 2040. This supplements the outcome of a techno-economic assessment for the CHEST battery in the Aalborg case study and puts the results of the current report into perspective of a business case.

2. Methods

The methods and approach of this initial market potential analysis is chosen because of the results of previous publications in the CHESTER project, that point to the fact that it is difficult to find good business cases for the technology on the short term. Therefore, a focus is put on the long-term potential rather than only the short term, to add new insights to the already generated conclusions. Due to this fact, the approach is not a standard market potential analysis, as it can be difficult to assess how the regulatory framework on EU level and on member state level will develop towards e.g. 2050. Hence, the approach in this study seeks to assess the fundamental technical justification for a technology as CHEST; the ability to improve the overall energy system efficiency and save some fuel consumption or other costs elsewhere in the energy system, resulting in a revenue from buying to selling the electricity. A potential to reduce fuel consumption in the overall energy system by introducing CHEST, is in this connection interpreted as a technical market potential.

The work performed here is based on a national energy system-level analysis. For that purpose, the EnergyPLAN simulation tool is applied to a number of national energy system models. The objective of the analysis is to identify the total technical potential of introducing the CHEST storage on a large scale. In the modelling framework a holistic approach has been chosen, including all energy-related sectors, i.e. electricity, heating, transport and industry. This opens the possibility of analyzing the dynamics of district heating integration of CHEST on a large scale, and the technical energy system potentials of this.

2.1. National scale energy system analysis

The study analyses the whole energy system on a national scale. It develops hourly balances for not only electricity but also for district heating, cooling, hydrogen and natural gas, which provides valuable knowledge regarding possible demand and generation mismatches. Since the entire energy system is modelled (both supply and demand), internal cash flows between consumers and suppliers are not necessary. This allows overcoming the challenge of determining or choosing future energy prices e.g. for electricity or heat, as these are calculated indirectly as a result of Capex and running cost.

Compared to an analysis on local level, a plant or a single production unit, the national scale energy system analysis can contribute with information on how a scenario or a technology will influence the rest of the energy supply system. There are many dynamics that the introduction of a new technology can interfere with, particularly if it provides services for several different parts of the energy supply system, e.g. heat and electricity.

2.2. The EnergyPLAN tool

EnergyPLAN is an advanced energy systems analysis computer tool designed for modelling and assessment of different scenarios and technologies with a focus on systems with a high share of renewable and fluctuating energy sources [1]. The tool works on an aggregated level, so that each plant or unit is defined by groups of plants of the same category using average specifications for that category, rather than defined by individual plants. It can be used for any scale of a system from city level to continent level but is most often used at regional or country level. [2]

The EnergyPLAN software is continuously being updated along with the technological development. It is developed by a research group at Aalborg University for application in scientific and research areas. It is available to download and use for free and there is a full documentation of the software and calculations provided along with various training material and tutorials. [3]

2.2.1. Modelling and simulation of scenarios

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. The inputs include the capacity of various energy resources, capacities and efficiencies of conversion and storage available and the different demands included in the model. See Figure 1. When the system simulation is run, EnergyPLAN seeks to meet all the energy demands using the available resources. This can be done in different ways reflected in several simulation strategies available, which is elaborated further in Section 2.2.2. In Figure 1 it can be seen how the different energy sources and demands (white and orange blocks) are connected (coloured arrows) through various conversion units (yellow blocks). For example, the power plants (PP) converts a fuel or steam input to electricity. Or a heat pump which converts electricity into high-temperature heat.

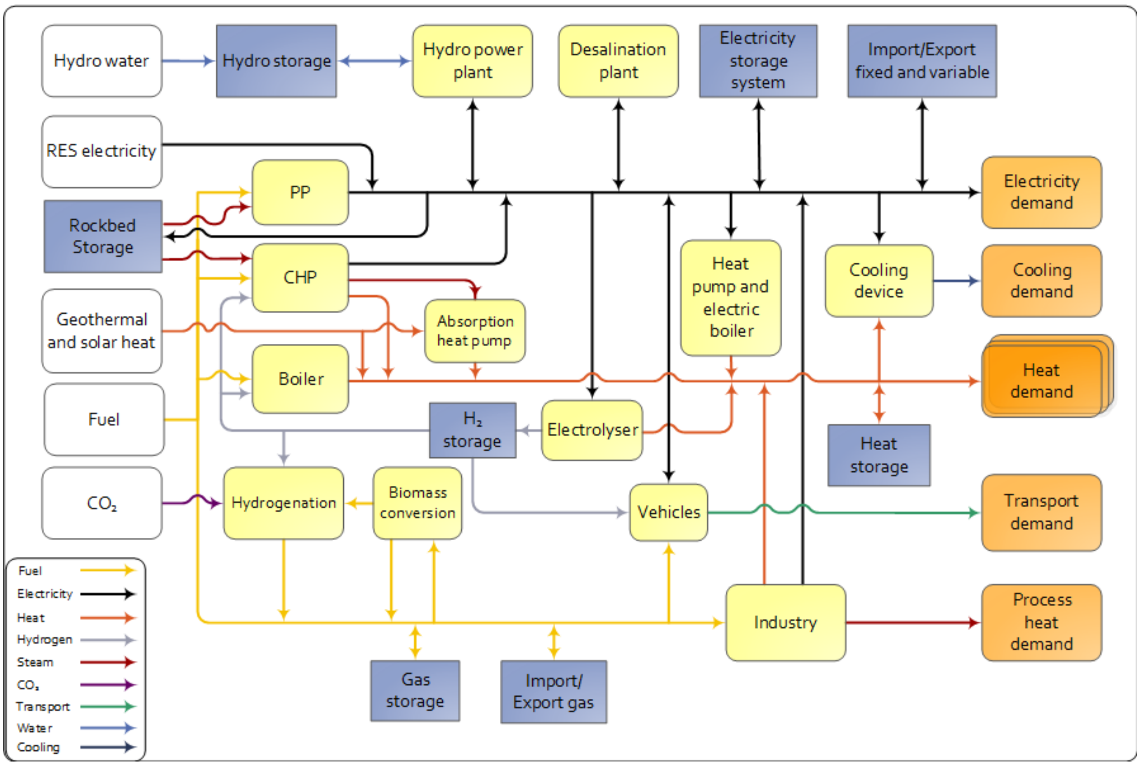

Figure 1 Overview of resources (white), conversion (yellow), storage (blue), supply infrastructure (arrows) and demands (orange) modelled in EnergyPLAN.

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. This hourly-based approach is particularly important when modelling storages because it enables to control 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.

2.2.2. Technical and economic simulation strategy

EnergyPLAN can be run with two overall strategies of simulation, 1) Technical simulation and 2) Market economic simulation. In addition to each of these two, there are some adjustments related to the operation of certain technologies, for example how electric vehicles should aim to charge. The common element of the simulation strategies is to decide on the priority of different supply technologies in supplying the defined energy demands.

The **technical simulation strategy** generally seeks to cover the demands giving priority to the energy-efficient production and conversion units. This means for example that in a system where there is both, a fuel boiler and a CHP present, the CHP capacity will always be given priority because it is more efficient than the fuel boiler. The fuel boiler will be activated when the operation of the CHP is technically infeasible. This could take place when the CHP plant is already operating at its full capacity or if there is an excess of electricity production already. This strategy represents any ideal operation where the units are operated to reach the less fuel-intensive solution and to identify a general potential of a technology that is desirable from a societal point of view.

In the **market economic simulation strategy**, the goal is to cover the demands using the supply units at the lowest marginal cost of operation. In the same mentioned earlier example with a CHP and a fuel boiler, the fuel boiler may in some cases be more economical to operate because of the electricity market price, taxes etc., compared to a CHP and thus, the fuel boiler will be activated instead of the CHP. This simulation strategy can work to represent how the energy system can be expected to operate in the short term with the current electricity market and energy tax structure. It can also be used to analyse the import and export with external electricity markets under different price level assumptions. This strategy, however, will typically neither represent the most energy-efficient nor the best socioeconomic way of operating various units of the energy system.

Both of the simulation strategies can determine the total system cost. In *both* cases the result is a socioeconomic total annual system cost, which include capital costs in the form of investment annuities and operating costs in the form of fuel costs, variable and fixed operating costs but not the connected taxes, which is seen as a redistribution within the society and not an actual cost. Electricity trade costs and revenue can also be included where relevant as well as CO_2-emission costs can be included.

2.3. Modelling of CHEST

In this section, the technical assumptions and the applied operation strategy of the CHEST storage is described.

2.3.1. Technical assumptions

In the modelling of scenarios with CHEST integrated a few technical assumptions have been made to represent its characteristics. In Table 1 the key technical assumptions for CHEST and the used alternative in Li-ion, have been listed. Charge, discharge and energy storage capacity of CHEST and Li-ion batteries are assumed to be the same when compared.

The COP of 4.0 in the heat pump for charging the thermal storage means that one unit electricity is consumed for every three units of heat from the heat source. This means that 25% of the energy output is from electricity and the remaining 75% is from the heat sources. In the discharge of the storage, 15% of the energy content is reproduced into electricity and 85% remains as heat, which can be dissipated into the environment or recovered for district heating or to cover other heat demands. There will 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 connection. However, the exergy level is reduced compared to the charging cycle, because a lower share of electricity can be regenerated.

The assumptions of the COP of the heat pump and the electric efficiency of the ORC depends on a range of parameters of which the temperature levels are central, but the choice of refrigerants, design of components and others are also important for the conversion efficiencies under given conditions. To give an example of a situation that could theoretically enable a HP COP of 4 as assumed could be heat source temperature set of 70 degrees supply and 40 degrees return, a storage temperature level of 160 degrees and a Lorentz efficiency of 65%. On the ORC electric efficiency a similar example to reach 15% could be a storage temperature of 160 degrees and a heat sink/output temperature of 60 degrees assuming a Carnot efficiency of 65%.

Table 1 Technical assumption for Li-ion and CHEST [8]

Parameter	Unit	Value
2020 charge and discharge capacity	MW-el	500
2020 energy storage capacity	GWh-el	25
2050 charge and discharge capacity	MWh-el	1.000
2050 energy storage capacity	GWh-el	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

The assumed values are generally optimistic compared to the previously conducted reviews in [8], [9] and [10], but it may be possible in the future in optimized installations and favorable conditions to achieve a similar performance of CHEST installations, and it might even be possible to reach higher. The assumptions can be adjusted in certain cases for sensitivity analysis, but the above mentioned are used if nothing else is mentioned.

In addition to these parameters, it has been assumed that the system is able to start and ramp to full load as well as stop production from full load within one hour. It is also assumed that there are no limits in the grid connection of CHEST or bottlenecks in the grids that limit its operation for either electric or district heating grids.

2.3.2. Implementation and operation strategy

Electricity only - free heat

This implementation strategy is to use the CHEST as electricity storage only. This assumes that the CHEST is located 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 to be available at all times and at sufficient 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.

Electricity and district heating exchange

This implementation strategy is to use the CHEST as electricity storage but with an exchange of heat with a district heating system. In this strategy, it is assumed that heat for the heat pump of CHEST will be sourced from the district heating system and that the heat production from the ORC will be injected back into the district heating system. This means that there will be a cost associated with the use of heat, but also revenue for heat production. The costs and the revenue will depend on the time of its occurrence because the marginal production unit in the district heating system changes from hour to hour, and they have different costs associated to them, just like what is the case for the electricity system.

In this case, the operation strategy of CHEST will be mainly to work in the electricity system, buying and selling electricity when that is profitable, and the exchange of heat will be a secondary product of the operation.

2.4. Parameters of comparison

In the technical market analysis, a list of different parameters is used as indicators for assessment and comparison of different scenarios, situations, system configurations etc. In the following chapter, these parameters are presented and described in relation to how they are used to interpret the results.

2.4.1. Primary energy supply

The primary energy supply (PES), given in TWh, is a sum of the resources used in the energy system through one year to supply the energy demands. It includes the 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, and a change in PES usually shows an improvement of the general system efficiency.

2.4.2. CO_2 emissions

CO_2 emissions, given in mega ton (Mt), is the sum of emission from the combustion of fossil fuel-based energy sources. A change in CO_2 emissions can be related to a reduction of fossil fuel consumption in PES. It can also be a result of a change in production mix where units with a higher share of renewable energy replace some fossil fuel-based units.

2.4.3. Excess electricity production

The critical excess electricity production (CEEP), given in TWh, is the amount of electricity that cannot be used in the energy system at the moment of production. In some cases, 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 and baseload power production units, there will almost always be some CEEP. 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. A reduction of CEEP will typically result in a reduction in PES.

2.4.4. Excess heat production

Excess heat production, given in TWh, is the amount of heat production in a district heating network, that will have to be dissipated into the environment or rejected in another way. This can occur when there is an inflexible heat source, such as solar thermal energy excess heat from industry. A change in the excess heat production indicates that the system can integrate more of the available heat sources. A reduction in excess heat will typically result in a reduction in PES.

2.4.5. Discharged electricity from CHEST

Discharged electricity from CHEST, given in TWh, is the amount of electricity that can be fed into the power grid to cover demands in the energy system. This is one of the key elements of a good business case as it will be a source of income for the operation of CHEST. A larger amount of discharged electricity will increase the foundation for a possible business case, even though other sources of income can also play a role.

2.4.6. Utilized heat from CHEST

The amount of utilized heat from CHEST, given in TWh, is the amount of heat produced in the operation of the CHEST ORC minus any eventual increase in excess heat by the specific implementation of CHEST. In some cases, there may not be a demand for the heat at the time where CHEST is producing heat, which means that some heat will be dissipated somewhere in the system. Either at the CHEST directly or somewhere else in the system if there are cheaper or more effective places, e.g. at a CHP plant or a solar thermal plant. The utilized heat from CHEST is an indication of how much heat can be sold to the district heating systems of the operation and will indicate whether there is a potential for increased heat sale.

2.5. Capacity potential screening

To assess the scale of the technical potential for CHEST in terms of installed capacity, a screening has been performed to estimate the total technical potential for CHEST. The potential has been estimated for the two different implementation and operation strategies, described under Section 2.3.2. The screening has been performed for six different countries: the six countries of the CHESTER consortium, Germany, Italy, Spain, Belgium, the Netherlands and Denmark.

For the electricity-only implementation, the boundary for the technical potential has been assumed to be a CHEST capacity that allows for integrating 50% of the total annual excess electricity production of the total system. 100% would be too high because there is a limit in the heat sources for the heat pump as well as a consideration of other solutions that may appear. The 50% also enables a higher number of operating hours and more continuous operation.

Regarding the district heating integration of CHEST, the boundary for the technical potential has been assumed to be the capacity that results in a peak excess heat production of the ORC of 50% of the low summer heat load of the district heating systems. This is to ensure that the ORC will always be able to discharge the heat into the district heating system. Even in a large scale introduction of CHEST, there will most likely not be CHEST systems installed in each single district heating system, and there by it will not be able to access all district heating. At the same time there will be solar thermal production, geothermal production and other excess heat sources in the mix, which do not allow for 100% coverage. In cases where a CHEST system produced electricity at times where there is no district heating demand, the CHEST will in practice operate as an electricity-only configuration.

The screening of each of the countries is performed using the EnergyPLAN tool, which is described in Section 2.2. For each of the countries of the screening a country energy system model is used. For Germany, the same model is used as for the second part of this analysis (see Section 2.6.2. For Italy, Spain, Belgium and the Netherlands, the Heat Roadmap model developed in the Heat Roadmap Europe project, for application with the EnergyPLAN tool, have been applied. The Heat Roadmap Europe project is documented in [9] and the country models for these countries are downloaded from the Heat Roadmap Europe website (www.heatroadmap.eu).

2.6. Case study of Germany

To elaborate on the technical potential from the energy system perspective, a detailed analysis of the CHEST integration in the case of Germany has been conducted. This will allow for concluding on the energy system types and configuration, in which CHEST will be particularly interesting, based on an analysis of the energy system dynamics of its introduction.

Germany has been chosen as a national energy system to conduct this study. The reason for selecting Germany is that this is a large centrally located in Europe country and its energy supply mix is close to the European average (see Figure 2). It is thereby seen a good representation of an average European location from a technical point of view. In addition, the CHEST prototype developed in this project is also located in Germany.

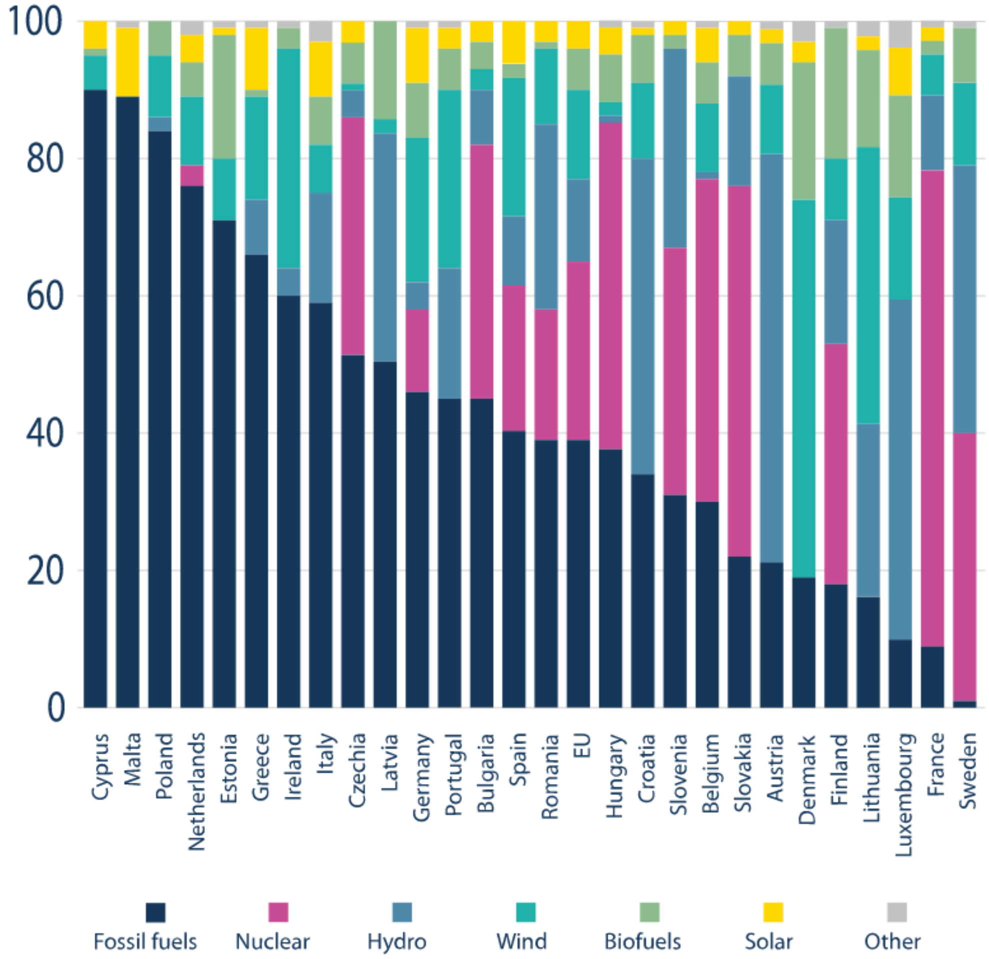

Figure 2: EU production of electricity by source and in 2019 (%) [10].

By choosing only one country rather than two or more cases, it is possible to run a more in-depth analysis of the dynamics and operation of CHEST. The resources it would take to include more countries in the model is not expected to be proportional to the added value of more countries. The weakness of having just one case which is the possibility of overlooking country-specific potentials is accommodated by sensitivity analysis where key elements of the energy supply mix are replaced to represent other regions better. Mainly in the short-term (2020-2025) in regions with significantly different climatic and geographic conditions compared to Germany, the approach has a weakness. In the short-term, there are known differences between countries, but in the future it can be expected that energy systems will change significantly, but it cannot exactly be determined how countries will develop their energy systems different from each other. So the 2050 scenario is seen as a better representation of all the European countries when taking the general uncertainty of the future development into consideration.

For the CHESTER project, three different country models for Germany are developed. The first model is a representation of the current energy system in Germany today in 2020, for the analysis of the potential for CHEST in the short-term future. The two other models are both representing 2050 but two different scenarios of the development of the district heating supply. Both have a significantly reduced amount of carbon emissions with a large share of renewable electricity supply and further electrified transport and heating sectors. The difference between the two 2050-scenarios is the representation of the district heating supply to assess the potential integration of CHEST in the future, depending on the development of the district heating supply. The first one is a business as usual scenarios for the district heating supply, where it is mainly based on combustion of fuel, as it is today. In the second scenario the supply is substantially electrified, compared to the one of today.

2.6.1. Reference model data

The data inputs for the model of the energy system of Germany which is used as a starting point for the analysis are partly adapted from a model developed in the framework of the IEA Technology Collaboration Programme (TCP) of Energy Conversion Through Energy Storage (ECES). The project Annex 28 - DESIRE focused on decentralized energy storage, and in connection to this, a model for EnergyPLAN was developed. This was based on the energy system of Germany in 2015 and designed to analyze the feasibility of different energy storage technologies and configurations, including battery storage and thermal energy storage. [3]

The model developed in the current study for the CHESTER project is an adjusted version of the model developed in the DESIRE project. This is done because the adaptation of the model from another project, with similar focus and use case, can save a lot of resources without significant loss of quality and because the results of the DESIRE project can then be compared with the new results from the analysis of the CHESTER project.

2.6.2. CHESTER scenario adjustments

The original DESIRE model has been adjusted to represent the current system in Germany of 2020 and two future scenarios of how the system could develop. The adjustments have because the original model is some years old and do not exactly represent the current situation. Due to low excess electricity production in the 2020 scenario, a variation of the 2020 scenario is introduced, called “2020 +100%”, whichis basically the 2020 scenairos, but with twice the capacities of wind and solar power. This is introduced to be able to assess a short term future situation where significant amounts of wind and solar power is implemented, because the current situation do not necessarily generate enough hours with excess electricity for electricity storage to be needed. However with additional 100% of the renewable electricity capacities, an excess electricity production will occur. This is a fictional scenarios, but it is made to be able to conclude on whether a soon and quick increase in the renewable capacity will generate a feasible situation for CHEST.

Regarding the 2050 model, the aim of the adjustments have been to represent the expected development towards the year of 2050. This has not been done with a purpose of favoring the CHEST system, even though this may be a result of the 2050 model that CHEST seems more feasible. However, the main adjustments from the 2015 model to the 2050 models are related to the expected development trends of increasing renewable electricity production and electrification of heating, transport, industry and fuel production. The overall change may be in favor of CHEST, but not all components of it, e.g. fuel production through electrolysis will generally be cometing with electricity storage. Complete documentation of the original data inputs can be found in [4].

In Table 2 a list of the concrete adjustments can be found. Below, the justifications for the adjustments are described. To take into account the uncertainty in the development of the district heating supply, two scenarios of how this can develop are included; 2050 Fuel and 2050 Electric. These are explained further in the following chapter.

Table 2 List of adjustments to the DESIRE model for the German energy system for application in CHESTER. In brackets ( ) the applied values of the "2020+100%" scenario.

Parameter	**Unit**	**DESIRE 2015**	**CHESTER 2020**	**CHESTER 2050 Fuel**	**CHESTER 2050 Electric**
Electricity supply					
Onshore wind	GW	41.7	54.0 (108)	201.9	208.0
Off-shore wind	GW	3.3	7.7 (15.4)	108.9	112.2
Solar PV	GW	39.6	51.5 (103)	297.0	306.0
Power plant (thermal)	GW	85.6	85.6	160.0	160.0
Transport demand					
Petrol	TWh	332	332	42.8	42.8
Diesel	TWh	220	220	155.0	155.0
Jet petrol	TWh	100	100	77.8	77.8
Electricity for transport	TWh	12.1	15.0	83.7	83.7
Electrolysis for fuel production	GW	0	0	9.7	9.7
Biomass gasification	TWh	0	0	126.0	126.0
Biomass hydrogenation, liquid fuel	TWh	0	0	162.5	162.5
Individual heating supply					
Coal consumption, boilers	TWh	28.3	28.3	0	0
Oil consumption, boilers	TWh	263.2	263.2	0	0
Natural gas consumption, boilers	TWh	466.0	466.0	0	0
Biomass consumption, boilers	TWh	90.8	90.8	121.0	121.0
Heat pumps production	TWh	6.7	11.7	359.5	359.5
Electric heating production	TWh	34.2	29.2	11.2	11.2
District heating supply					
District heating demand (incl. loss)	TWh	159.6	159.6	234.6	234.6
Combined heat and power	GW-e	50.1	50.1	50.1	10.0
Heat pumps	GW-e	0	0	0	15.0

The electric capacities of renewable power production have been updated for 2020 [5] (Reference) based on data from Fraunhofer Institute. The capacities of onshore wind, off-shore wind and solar PV for the 2050 models are scaled based on the renewable energy development trend projected in the DESIRE project [4], to a level where the excess electricity production in the system (see more about excess electricity production (EEP) in 2.4.3) is equivalent to 10% of the total annual electricity demand in an island mode analysis. That is to keep a comparable level of fluctuating renewables in future models. Thermal power plants are assumed to be converted so that 50% use gas and 50% use biomass. The capacities are adjusted in both 2050 scenarios to be able to cover all new electricity demands at all times.

The share of direct electric transport has been increasing rapidly in the last few years in Europe, which is also the case in Germany [5]. From 2015 to 2020 the amount of battery-electric cars in Germany increased from about 19.000 vehicles to 137.000 by August 2020. If each car charges 5 MWh per year, this is an increase of about 0.5 to 1 TWh in total. In addition to this, there is an increase in plug hybrid electric vehicles and rail transport. The total of electrified transport in 2020 has been assumed increasing from 12 to 15 TWh. In the two 2050 scenarios, the transport sector is identical, and values have been adopted from [6]. Here, there has been a focused electrification of the sector through direct electrification, reducing the use of fossil fuels. Moreover, half of the remaining fuel consumed for transport is assumed to be electrofuels. Electrofuels are synthetic fuel made by upgrading gasified biomass using hydrogen. Excess heat from the electrolysis is assumed equivalent to 5% of the hydrogen production, feeding into the district heating systems. The capacities of electrolysis, gasification and hydrogenation are set to cover the production of hydrogen and electrofuels demanded.

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 district heating [7]. In the present study, it is assumed that the overall heat demand in buildings in 2050 to be reduced to 75% of the 2015 demand. At the same time, it is assumed that the district heating coverage of the total demand is increased from 15% in 2015 to 30% in 2050. These projections have been reduced in this analysis to demonstrate more rational estimates since the findings of the Heat Roadmap Europe represent rather ideal and not necessarily the realistically achievable levels.

In the individual heating supply, it is assumed that the overall demand is maintained in 2020, but with a share of the demand in 2015 covered with direct electric heating, in 2020 covered with heat pumps. 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 [6].

District heating supply is maintained in 2020. In the 2050 scenario, coal and oil supply is replaced with biomass and gas, so the total fuel mix is 50% gas and 50% biomass. There is in both 2050 scenarios also a share of industrial excess heat and solar thermal heat. The two different 2050 scenarios differ on the main components of heat supply:

- In the 2050 Fuel scenario, the supply system for district heating is maintained as in the 2020 scenario. The district heating production is based on fuel boilers as well as combined heat and power (CHP) plants, which is basically utilizing excess heat from power plants, at the cost of a cut in the electric efficiency.
- In the 2050 Electric scenario, the capacity of CHP plants is reduced and replaced with a capacity of heat pumps. This results in a higher thermal efficiency of the thermal power production and makes room for electrified heat sources. 9 GW-electric of heat pumps are introduces, with a COP of 3, equivalent to er thermal output of 27 GW. In this scenarios, there is a bit higher electricity consumption in the model, which results in slightly higher capacities of renewable electricity generation to meet the same 10% CEEP.

2.6.3. Scenario description

The scenarios based on the described input data were created and simulated and the findings are presented in the following section. The figures represent the basic scenarios without the implementation of CHEST, to illustrate the systems and differences between them. In Chapter 3, the results of introducing CHEST into these scenarios will be presented.

Figure 3 shows the comparison between the three scenarios on the primary energy supply (PES). This shows how a large share of fossil fuels have been replaced by renewable energy and biomass. It can also be seen that the total PES has been reduced even though the final demands are almost the same. This is caused by the system being more efficient because of the high electrification which results in lower thermal losses in connection with the combustion of fuels.

The two 2050 scenarios are in this perspective almost identical because the district heating is a relatively small part of the overall supply.

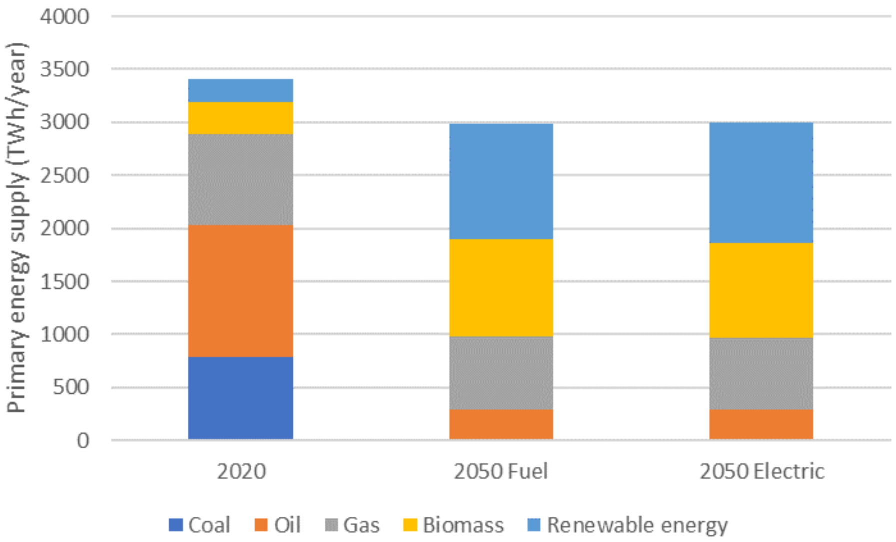

Figure 3 Primary energy supply in the three scenarios.

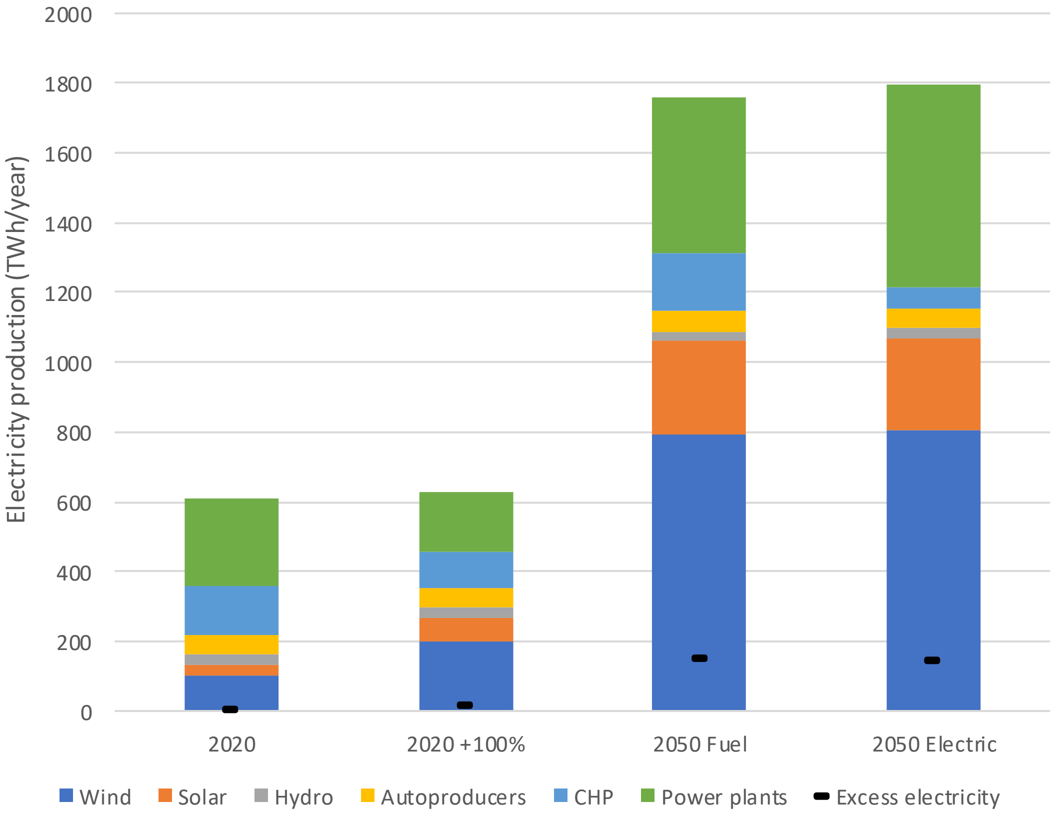

Figure 4 shows the comparison of electricity production, and here it is clear that the 2050 scenarios are more electrified than in 2020 as the total electricity production is almost three times as large in 2050. This is mostly due to the large increase in production from wind and solar. The thermal power plant is still producing roughly the same amount of electricity as in 2020 even though the wind is replacing a lot of production. This is because there are still times without wind and solar PV production and the electricity demand needs to be covered from other conventional sources. A variation of 2020 is introduced where the wind and solar PV capacities are doubled compared to the 2020 reference. The excess electricity production (EEP) in the scenarios can also be seen. The EEP is an indication of the need for balancing of the electricity system from a technical point of view. In 2020 it can be seen that the EEP is close to 0, which means that there is very little basis for electricity storage in this technical perspective. This is the reason for introducing a variation with twice the capacity of wind and solar PV for the purpose of the analysis. The variation can show how the situation could be in 5 years from now as increasing amounts of wind and solar PV is expected to be deployed in the coming years.

The two 2050 scenarios are still similar, but it can be seen how the CHP plants operate fewer hours in the 2050 Electric scenario but the condensing power plants operate more.

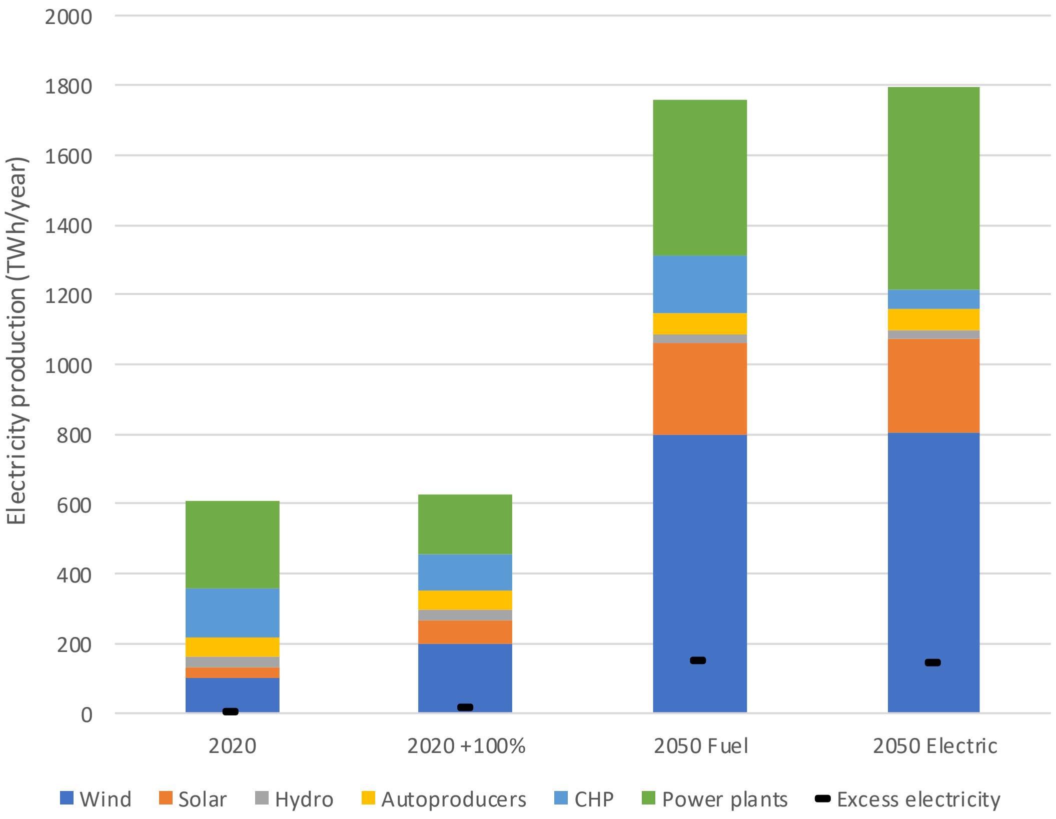

Figure 4 Electricity production in the three scenarios.

In Figure 5 the district heating production of the three scenarios can be seen. The total district heating production of the 2050 scenarios increased by ca. 45% in respect to 2020, despite it was expected to double in accordance with the district heating coverage that doubled. That is due to the reductions in heat demand which has been assumed from 2020 to 2050. The excess heat production is a result of the electrolysis and the assumed excess heat from that process, where 5% is assumed utilized in district heating. It can also be seen that the 2020 and 2050 Fuel scenarios are very similar except the total production. The largest difference between 2050 Fuel and 2050 Electric, is the large replacement of CHP production with heat pump production.

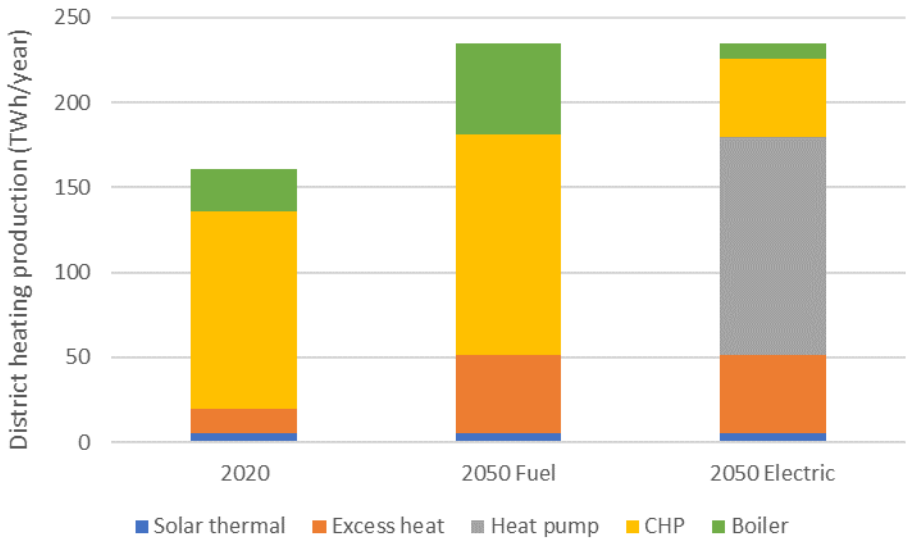

Figure 5 District heating production in the three scenarios

In Figure 6 and Figure 7 the annual distribution is shown of the two 2050 scenarios using monthly averages. It can be seen that the solar thermal and excess heat are identical in both scenarios as their outputs are not affected by the introduction of heat pumps. However, the production of the CHP and fuel boiler production is highly affected, mainly in the winter months where the heat pumps replace the majority of CHP.

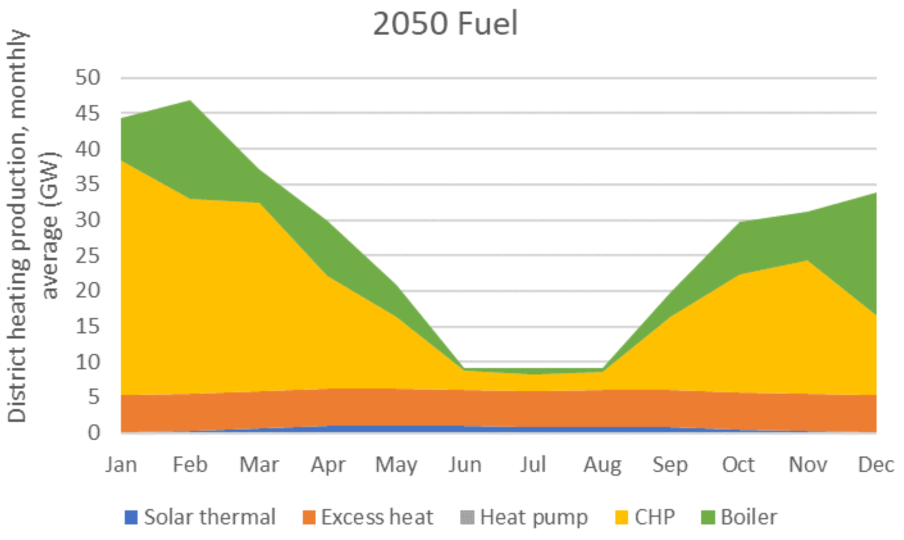

Figure 6 District heating distribution of monthly averages for the 2050 Fuel scenario.

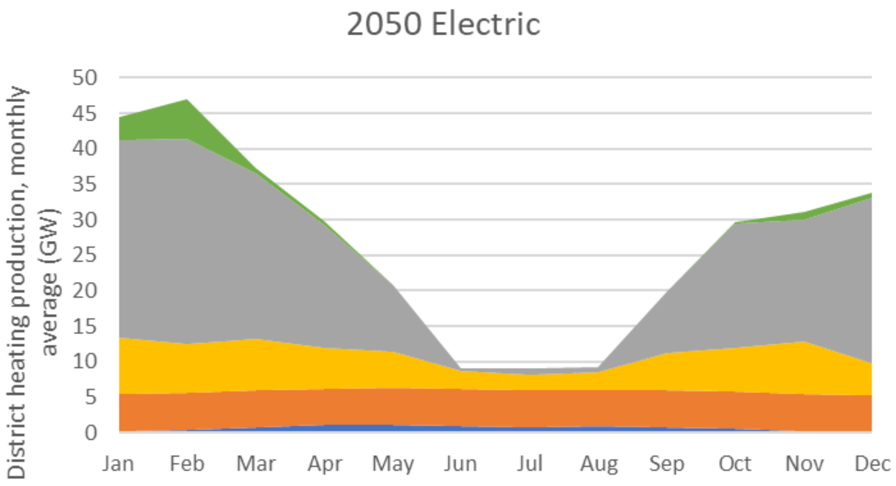

Figure 7 District heating distribution of monthly averages for the 2050 Electric scenario.

2.7. Sensitivity analysis

To uncover what the results are sensitive to, a number of analyses have been made, where different parameters or assumptions have been adjusted to illustrate the change of results in case of different situations.

2.7.1. Wind to PV

To represent a different geographical region in terms of renewable electricity production, the wind power production capacity has been reduced by one third, and replaced with solar PV capacity with an annual production corresponding to the decrease of the wind power. The change will change the production profile of total electricity production including the CEEP, hence influence the operation of the storage.

2.7.2. PV to hydro

Similar to the analyses described above this analysis is to represent another geographical region. Here, the solar PV capacity has been reduced by one third and replaced by an increase in the hydropower production corresponding to the reduction in the production of solar PV. The change will change the production profile of total electricity production including the CEEP, hence influence the operation of the storage.

2.7.3. Flexible demand

To represent an increase in the flexibility of the existing electricity demand, 25% of the annual electricity demand, corresponding to 149 TWh, has been converted to a one-day-flexible demand. This means that the demand can be moved within one day. This is based on the built-in function in EnergyPLAN to model this. Flexible demand will move the electricity demand away from peak demand hour and most likely reduce the CEEP.

2.7.4. Smart transport

Electrification of transport is already largely implemented in the scenarios, but in this analysis, the flexibility of the charging scheme is implemented to 25% of the electric vehicles. This represents a situation where plugged-in vehicles are allowed to charge flexibly to a certain extent, to reduce peaks in electricity demand.

2.7.5. Electric boilers in DH

In this analysis 6.3 GW electric boiler capacity is implemented equivalent to 10% of DH peak demand. This will allow the DH systems to absorb more excess electricity to produce heat. This will reduce the excess electricity production, but also supply more heat based on renewable electricity for the CHEST as a heat source.

2.7.6. CHEST efficiency

In this analysis, the efficiency of the CHEST is analysed for its sensitivity. This is done by reducing the ORC unit electric efficiency from 15% electric output to 12% electric output. This is an example of reduced efficiency of the CHEST. It could also have been reduced efficiency of the heat pump or losses of the thermal storage, and based on the simulation approach, the results of such will be similar to this one. The assumed 15% is in the high end of the scale of the potential ORC operation, but not completely unrealistic to achieve. However it might not in all applications reach that level, so the more conservative estimate is here tested. It will reduce the potential to replace the fuel in the electricity supply.

2.7.7. Existing battery storage

In the energy system model, there is no dedicated power-to-power storage included, except the existing pumping capaccities in hydro power plants. In this sensitivity analysis, the influence of assuming an existing capacity of an independent grid level electric storage is analyzed. The storage is identical to the Li-ion battery analyzed in the scenarios, with 1 GW charge/discharge capacity and 50 GWh storage capacity and with a 95% round trip efficiency.

3. Results

In this chapter, the main results of the analyses are presented. In the first part, the results of the implementation of CHEST in the different scenarios are presented, elaborated and discussed. In the second part, the results of the sensitivity analyses are presented and the implications of this discussed.

3.1. Screening of capacity potential

The results of the screening of the technical market potential in the two different ways of implementing CHEST, in terms of installed capacity, can be seen in Figure 8. It can be seen that the scale for the potenital of the electricity-only storage integration is many-fold larger than the potential allowed by the district heating integration. This is due the the electricity demands being larger than the district heating demands in general, but also that there is a larger energy flow on the heat side of CHEST. E.g. 1 MWh electricity produced by the ORC, but approximately 5 MWh heat produced at the same time.

To scale the results to the EU level, the size of Germany compared to the rest of the EU can be used as a point of reference. For both electricity production and population, Germany accounts for approximately 20%. Hence, the total technical market potential for CHEST in the EU is between 150-200 GW for electricity-only and 4 GW in integration with district heating. Large parts of these potentials however, may be occupied using other competing technologies, even if the CHEST technology show to be economically feasible.

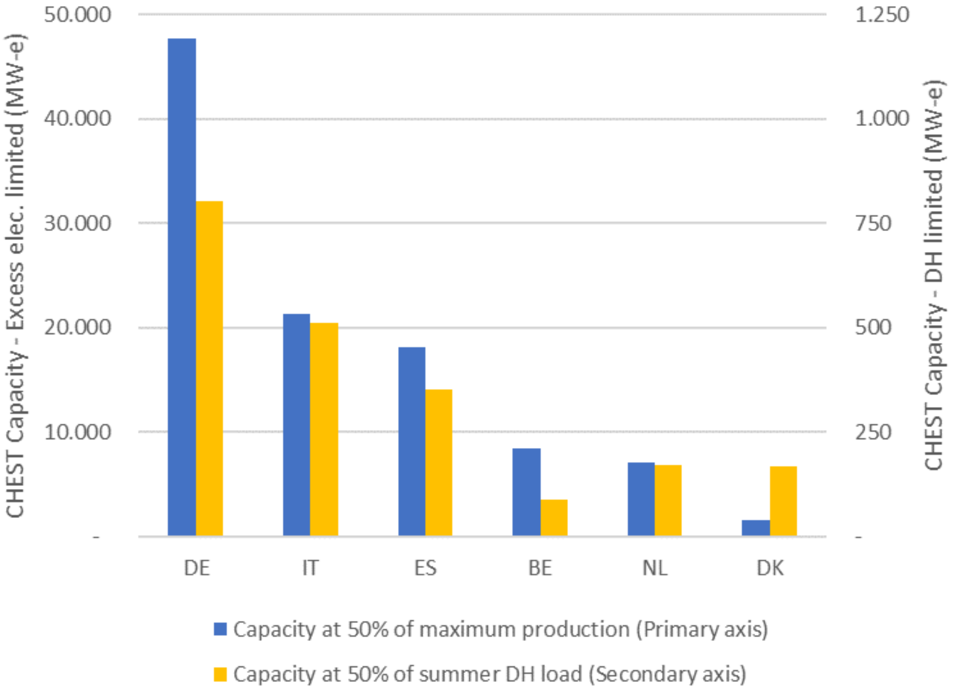

Figure 8: Main technical results of the capacity screening for the selected countries in 2050 for the two diffent ways of implementing CHEST.

3.2. Technical feasibility assessment

In this part, the results of the implementation of CHEST in the core scenarios described will be presented and discussed.

3.2.1. Current situation – Short-term future

The results of the implementation of CHEST in the current 2020 energy system of Germany and in a variation with 100% additional production from wind and solar power, can be seen in Figure 9. It can be seen that in the current system of 2020 the storage is almost not activated. This is due to the technical systems approach, because in the energy system of Germany today, there are almost always some thermal power plants operating that can balance out the fluctuations of the existing wind and solar power production. This results in a very low technical need for storage of electricity because reducing the production in a power plant is more efficient than storing the excess electricity. There has to be some excess production in some hours of the year which can be stored and replace less efficient production in other hours, for storage to be effective. There might be limitations or bottlenecks in the electricity grid which could also make storage useful. However, EnergyPLAN does no include the possibility of analyzing the electricity network and it is in most cases more efficient to strengthen the power grid at bottlenecks than solving this using electricity storage.

In the 2020 +100% variation, the capacity of wind and solar has been increased with 100% to illustrate the effect that might occur in the near future as more wind and solar power production is expected. Here it can be seen that the storage is activated and used. The additional fluctuating power production from wind and solar PV causes more hours to have EEP which creates a need for flexibility, giving the reason for the storage being activated.

The three storage configurations are compared on storage charge and discharge, change in EEP and change in PES. In all the three storage configurations, the electricity charged into the storage is very similar. This is because the capacities of the storages are the same and that they are applied in systems with the same amount of EEP. The change in EEP is also very similar because this coincides with the charged electricity in these cases. The discharged amount of electricity is larger for the Li-ion storage due to the higher power-to-power ratio of 0.95 compared to 0.60 for CHEST in this case. The last indicator in the figure is the reduction of PES in the total energy system, which is the primary indicator in this analysis. It can be seen that the reduction in PES is largest in the Li-ion configuration and a bit smaller in the CHEST El-only configuration. In these cases, both technologies work to store excess electricity from wind and solar PV to replace production at thermal power plants at times where there is less renewable production available. The reduction in PES is here about twice the discharged power from the storages because the fuel input for the thermal power plant is larger than the power output due to the fuel-to-power conversion efficiency at thermal power plants.

In the last storage configuration, where CHEST is integrated with district heating, there is a negative reduction of PES, which means that there is an increase in PES compared to a situation with no storage. This is due to the temporal operation of CHEST and the simultaneous heat supply units.

When the CHEST is charged, at times with excess electricity, with the heat pump, the heat supply from the district heating system is covered using a fuel boiler, because the CHP do not operate when there is excess electricity already. When the CHEST is discharged, when there is low production of renewable electricity, the heat output from the ORC will replace heat from a CHP, because a CHP operates at the same time as CHEST, when there is no excess electricity. This means that CHEST uses a fuel-based source through the district heating when being charged, but is not replacing any fuel when discharging.

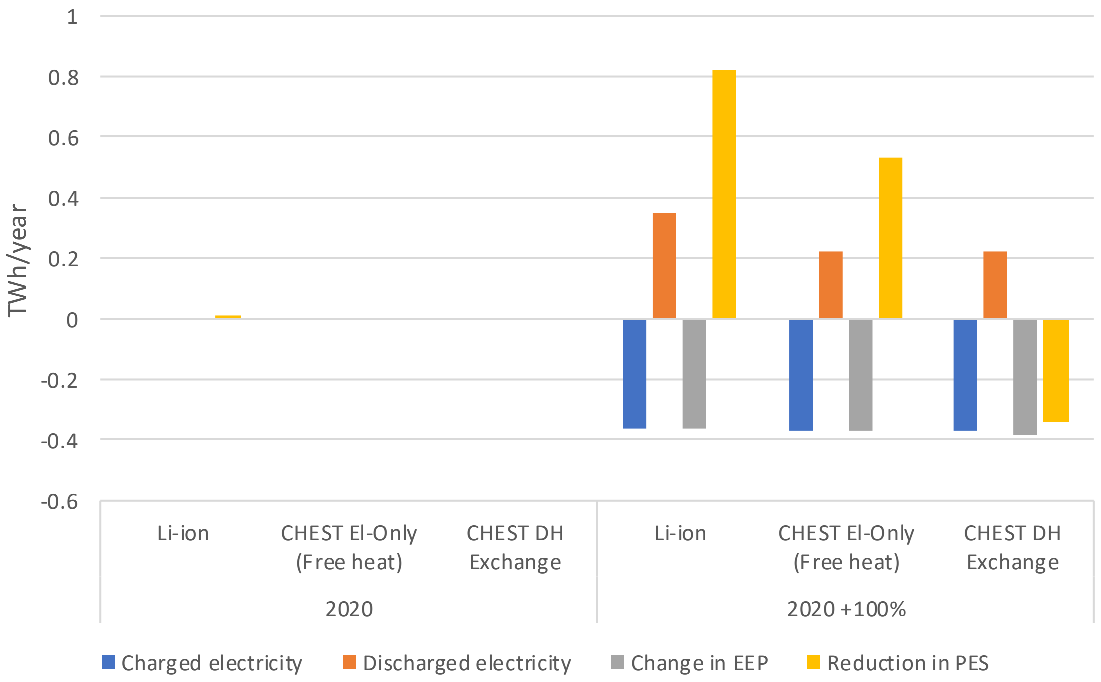

Figure 9 Results of CHEST implementation in the current system.

The results indicate that there is not a very big need for CHEST, or electricity storage in general, on a national system level from a technical perspective. There might be grid limitations or bottlenecks that create local needs for balancing, though. There might also be economic incentives to make investments in electricity storage, based on local tariff structures, tax structures, subsidy schemes or similar. However, these do not necessarily mean that there is a technical basis for system-wide storage implementation.

In the short term future, where we expect the RE electricity production to increase, there is some potential for electricity storage from a technical perspective. As it was explained, there is a potential for reducing the primary energy supply of the total system by introducing an electricity storage capacity of 500 MW and 25 GWh. The simulation shows an operation pattern equivalent to 70 full storage cycles each year.

Regarding the integration of CHEST in 2020 however, there is not found a general technical potential, even with the increase in renewable electricity production, due to the dynamics explained above. In the current district heating supply CHEST do not show to be very effective in integration. The change of district heating heat supply can be a long transition, as the investments in thermal power plants are large and runs for two, three or even four decades. As long as the current infrastructure is in place, producing excess heat from power production through CHP, the potential for CHEST might be limited to district heating systems where a transition can take place earlier. The transition towards 2050 and the potential for CHEST in this is discussed further in the following chapter.

3.2.2. Renewable energy system – Long-term future

The results of the analyses of the 2050 scenarios are shown in Figure 10. The results for the two scenarios for the German energy system, 2050 Fuel and 2050 Electric can be seen for the three storage configurations.

It can be seen that 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 a lot by the way DH is supplied. This 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. If CHEST can come with a lower investment and/or operation cost compared to the Li-ion battery, it might be economically competitive, however, but that is not analysed here.

When it comes to the results for the CHEST DH-exchange configuration, the picture is different. The amount of electricity charged into the storage and the electricity discharged and supplied into the electricity grid remains the same as 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. 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.

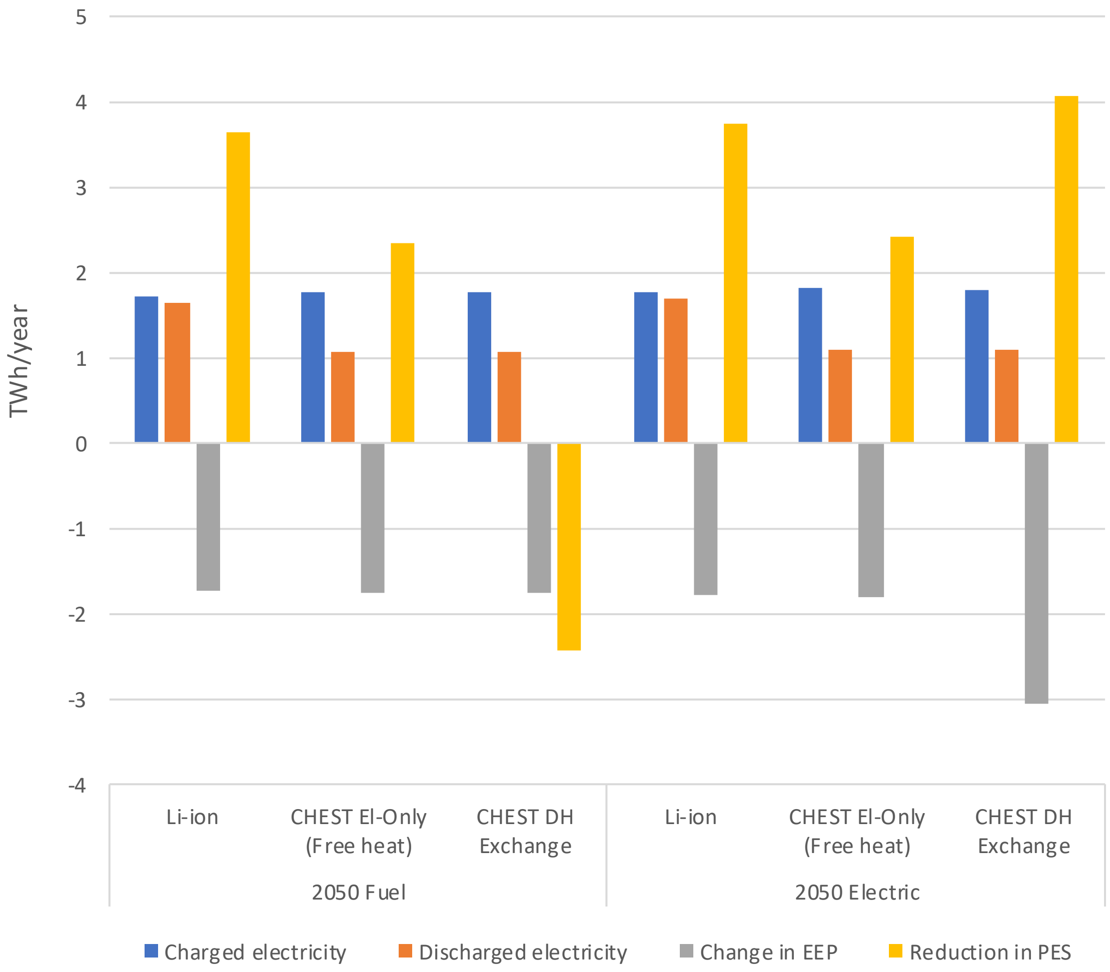

Figure 10 Main technical results of the two 2050-scenarios for the relevant storage configurations, Li-ion, CHEST El-only and CHEST DH-Exchange

In Table 3 the changes in the energy supply caused by the implementation of the CHEST storage configurations can be seen. It can be seen that the El-only configurations in both scenarios only results in changes to the electricity supply, whereas the DH-exchange configuration results in changes in both electricity and district heating 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 district heating. Only to some extent, because the DH-exchange configurations also generate a surplus heat.

In the DH-exchange configuration of the 2050 Fuel scenario, it can be seen that 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, it can be seen that 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 10, that the introduction of the CHEST El-only configuration in the 2050 Fuel scenario causes an increase in PES.

In the 2050 Electric scenario, it can be seen that EEP is utilized to replace CHP production (-2.1 TWh) but without an increase in PP production. In the district heating 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 district heating 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 10.

Table 3 Resulting changes in the energy supply for electricity and district heating 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	RES	0	0	0	0
	Autoproducers	0	0	0	0
	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	RES	0	0	0	0
	Excess heat	0	0	0	0
	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

3.2.3. Sensitivity analyses

In Figure 11 the main results of the sensitivity analyses can be seen. The assumptions for these can be found in Section 2.7. The figure shows the reduction in primary energy supply after the implementation of the particular storage configuration. The positive result of the CHEST DH-exchange in the 2050 Electric scenario, is assessed for its sensitivity to a number of uncertain parameters and system assumptions. The first two columns in the figure are identical to the ones of Figure 10 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 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 cause, 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 for CHEST, even though it will also reduce the EEP. This means that the benefit of the further electrification of the DH system, where the CHEST is integrated into, is larger than the negative effect of the reduced EEP. In the parallel case with the Li-ion, the reduction is slightly lower with electric boilers in place.

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 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.

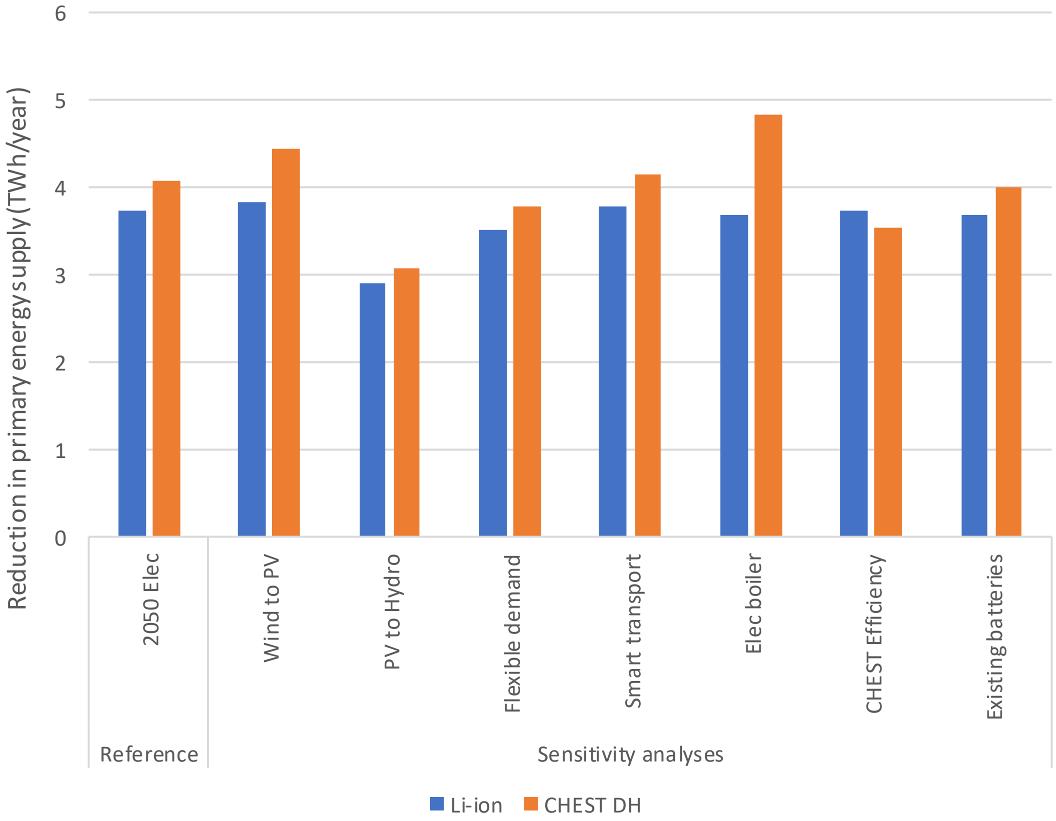

Figure 11 Results of sensitivity analyses to the 2050-Electric scenario for Li-ion and CHEST DH-Exchange

4. Summary and conclusions

The purpose of the study is to investigate the technical market potential of the CHEST technology. The technical market potential is in this connection understood as the maximum foreseeable installed capacity and the possible reduction of primary energy supply needs of the overall energy system at national level, by introducing large-scale capacities of the CHEST storage solution. CHEST in this national energy system context, accumulates and stores excess electricity from RES and discharges it back in form of both, heat and electricity at the time of increased demand.

4.1. Summary of the approach

The main scope of the analysis is to determine the technical potential introduction of the CHEST storage technology at the national energy system level, where the potential is assessed for a short-term market (2020-2025) and a long-term market (2050). An initial analyses covers a screening of the technical market potential in terms of installed capacity for six different countries. In a detailed analysis of the energy system of Germany, two different scenarios of the development for district heating supply towards 2050 have been included. The first one represents the district heating system as per today, supplied mainly using CHP, and in the second scenario the district heating supply is based on heat pumps.

The CHEST technology is analyzed in two basic configurations in the study; firstly, as electricity-only storage, where there is no exchange with the district heating and the heat is assumed to be an excess heat source. Secondly, a configuration where the CHEST is integrated with district heating supply in addition to the electricity system. Here, the heat for the CHEST heat pump is assumed to be sourced from the district heating system and the heat output of the CHEST ORC is assumed to be fed back into the district heating system. As an alternative battery technology, Li-ion battery storage of the same capacity is analyzed as a third storage configuration.

The study is based on models of the energy system of Germany. Germany is a large and centrally located country in Europe and was chosen because the results will represent well the largest parts of Europe. However is to be considered that regions with significantly different climatic and geographic conditions compared to Germany, in the short-term analysis (2020-2025) may not be well represented. On the other hand, the very diversified electricity and heat system with a high penetration of renewable energy demonstrate a good representation of the aimed future systems in entire Europe. The model for Germany is based on a previous study on energy storage but updated specifically for the CHESTER project. The model is implemented into the energy systems analysis tool EnergyPLAN, which is also used to perform simulations for different storage configurations and scenarios. The models and simulations include all energy-related sectors and infrastructures and the hourly operation and dynamics between the different sectors and supply units.

4.2. Results and conclusions

The initial long term screening of the total potential in terms of installed capacity shows that there is a significant technical potential for electricity-only storage of up to 150-200 GW in the EU, however the potential when it comes to district heating integrated systems are much smaller, about 4 GW in total in the EU. In both cases this total technical potential should be seen as a maximum of what can be technically achieved. The economic potential will be smaller, and likely much smaller, than what is indicated here.

The results of the detailed analysis of the 2020 scenarios shows that the CHEST is not able to reduce the primary energy supply because there is only very little excess electricity available due to a relatively low penetration of fluctuating renewables. There may be a technical potential in local regions, e.g. due to electricity grid limitations, but that is outside the scope of this study.

In the short-term future (2020-2025), with an expected significant increase in renewable electricity supply, there will be an increase in the technical potential for electricity storage, including the CHEST technology. However, in comparison to Li-ion storage, the CHEST system shows a lower reduction in primary energy supply as electricity-only storage. The results from the integration with district heating in the existing district heating production mix, show that CHEST will not be efficient in its integration because the operational dynamics of CHEST and CHP units will be counterproductive in the district heating system. The marginal district heating production unit, at times when CHEST is charged, is predominantly fuel boiler production, which increases primary energy supply. Conversly, it cannot effectively replace fuel consumption, at times when CHEST is discharging, because at these times there is excess heat from CHP, resulting in a net increase in primary energy supply.

In the long-term perspective (2050) however there is technical potential integration of electricity storage including the CHEST technology.

As for the short-term analysis (2020-2025), the electricity-only configuration of CHEST achieves a reduction in primary energy supply, but lower than the Li-ion storage, due to the lower power-to-power ratio. In the configurations of CHEST integrated with district heating, the results depend on the assumed scenarios for the development of district heating production. In the scenario where district heating is produced mainly by CHP plants, the result is a negative reduction in primary energy supply, as in the short-term analysis. However, for the scenario where district heating production is based on efficient power-to-heat units, CHEST achieves a large reduction in primary energy supply. The reduction here is larger than the corresponding reduction in the Li-ion configuration, even though the power-to-power ratio is only 60% compared to 95%. This is due to a synergy in the integration of the CHEST system with an electrified district heating supply, and the CHEST generating an added value to the district heating system.

Sensitivity analyses show that further electrification of the district heating supply, using direct electric boilers to supplement heat pumps, will increase the technical potential of the CHEST system. The sensitivity analyses also indicate that if the electric efficiency of the CHEST ORC is reduced from 15% to 12%, the technical potential introduction will tip so that Li-ion battery storage (also in the electrified district heating supply), will provide the largest reduction of primary energy compared to CHEST.

In an appendix to the main report, an economic case study has been provided, which analyses in detail the business case of a concrete case (since so far, in this phase 1 of the study, the economic variable has not been considered yet). The results of this initial case study indicate that the business case is better in the future where electricity prices can be expected to change, but still that it can be difficult even in the long-term to reach a profitable case due to high investment costs of the CHEST system. This underlines the necessity of looking closer into the economic aspects and the relation between the operational and the capital costs, which will be pursued further in the upcoming work.

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6. Appendix A

This appendix contains an additional analysis on the economic assessment of the Aalborg case study which was reported in D4.5. The analysis was carried out with future price profiles of the spot electricity market in Denmark for the year 2040. Due to the predicted higher fluctuation of electricity prices, the economic assessment of the Aalborg case study is thought to become much better. Since the future electricity price profiles were made available at the very end of October 2020, this analysis could not be implemented in D4.5, but is reported in this deliverable.

6.1. Introduction

In D4.5, simulation results and the outcome of a techno-economic assessment for the CHEST battery in the Aalborg case study were presented. This business model involved exchanging electricity with the national grid in so-called arbitrage and the participation in both the Danish spot and regulation market. It was shown that the annual profit from shifting the electricity export to hours with more favorable electricity prices is currently negligible compared to the investment costs of the CHEST system which cannot be paid back within the technology lifespan. This is mainly due to the unfavorable electricity prices and the tax scheme currently in place. Given the expenses for operating the CHEST system additional to electricity import price (fees, taxes operation and maintenance (O&M) costs), a significant gap between purchase and sale of electricity is necessary to make a profit. Since the prices in the two abovementioned electricity markets rarely show such differences, the operation time of the CHEST system is very limited and this leads to a very low annual profit.

However, an increase of the demand for electrical energy storage is expected in the coming years due to the increased capacity of renewable electricity sources in the electricity supply sector. This will certainly change electricity prices and the tax schemes for electrical energy storage.

In October 2020, two price profiles of the future spot electricity market in Denmark were made available by Danish transmission system operator (TSO) Energinet. These profiles are predictions of the spot electricity market in the year 2040 and they are based on calculations/simulations made by Energinet. The first profile considers a situation without or with the insignificant appearance of Power-to-X (PtX) technologies (herein after referred to as “2040-NoPtX”) while the second profile includes the (significant) use of PtX technologies in the future Danish energy system (herein after referred to as “2040-InclPtX”). Since the profiles themselves are confidential, they cannot be shown here. However, it can be said that these profiles are characterized by higher average electricity prices and by higher price fluctuation compared to the profile of the spot electricity market of 2016 used in D4.5 analysis. This has the potential to considerably improve the business case for a CHEST system.

6.2. Brief description of the analysis

The analysis of the business case for the Aalborg case study was basically the same as reported in D4.5, i.e. the TRNSYS model that was developed in T4.2 and adapted to the Aalborg case study, was used for the simulations reported here. The same O&M costs (10 €/MWh$_{el}$ for the HP and

15 €/MWh_{el} for the ORC) and the same tax scheme (21.53 €/MWh_{el} as Buy-Addon and 0.52 €/MWh_{el} as Sale-Addon) were considered which means a total required price difference between purchase and sale of electricity of 47.05 €/MWh_{el}. As was shown in D4.5, this price difference between purchase and sale of electricity can be reduced in the control of the CHEST system. This is due to the fact that the P2P ratio is considerably higher than 100 % for the boundary conditions of this case study which means that the amount of sold electricity is higher than the amount of purchased electricity. The lower price difference between purchase and sale of electricity of 36.19 €/MWh_{el} applied here in the control of the CHEST system increases the charging and discharging hours of the CHEST system and hence, this gives more opportunities to sell service on the market.

Two runs of simulations were done:

- simulations for the participation of CHEST only in the spot electricity market to better directly compare the old (2016) and new (2040) profiles with each other
- simulations for the participation of CHEST in both the spot electricity and the regulation market

Note: the electricity price profile of the tertiary regulation market was the one from 2016 in any case since there is no profile for 2040 available.

The buy-limit was constant during the whole simulation, which means that there is a fixed price threshold below which electricity is purchased (buy-limit) and, because of the given price difference in the system control of 36.19 €/MWh_{el} (see above), also a fixed price threshold above which electricity is sold (sale-limit). In the settings of the simulation, only the buy-limit is an input since the sale-limit is automatically given by the beforementioned buy-limit + the price gap of 36.19 €/MWh_{el}. The size of the CHEST system was the same as reported in Table 2 of D4.5, i.e. a HP and ORC nominal electrical power of 5 MW_{el} each and a total HT-TES storage capacity of 1,471 MWh_{th}. For more details on the sizing and the settings, please refer to D4.5.

After the two runs of simulations, further simulations were carried out with flexible (time-dependent) settings concerning the buy-limit. However, only small improvements concerning the annual profit or the required HT-TES storage size could be achieved. Thus, only the most important results from the two abovementioned runs of simulations are reported in the following.

6.3. Results

Figure 12 shows the annual profit that is generated by the CHEST in the first run of simulations, i.e. for the participation in the spot market only. As was said above, the buy-limit set in the control of the CHEST system was fixed. Different values for the buy-limit were applied and the profit shown in Figure 12 is the highest one achieved for the respective profile.

As can be seen from the figure, the annual profit for the spot market electricity price profile of 2016 is very low which is due to the low price fluctuations. In contrast to that, the annual profit is considerably higher for the price profiles of 2040 for the same CHEST size, settings and boundary conditions. Furthermore, it can be seen that the use of the profile “2040-NoPtX” results in a higher annual profit than the use of the profile “2040-InclPtX”. This is probably due to the fact that both profiles are almost identical concerning higher electricity prices, but the profile “2040-NoPtX” has more hours with very low electricity prices and this gives the possibility of cheaper purchasing of electricity for heat pump operation compared to the profile “2040-InclPtX”.

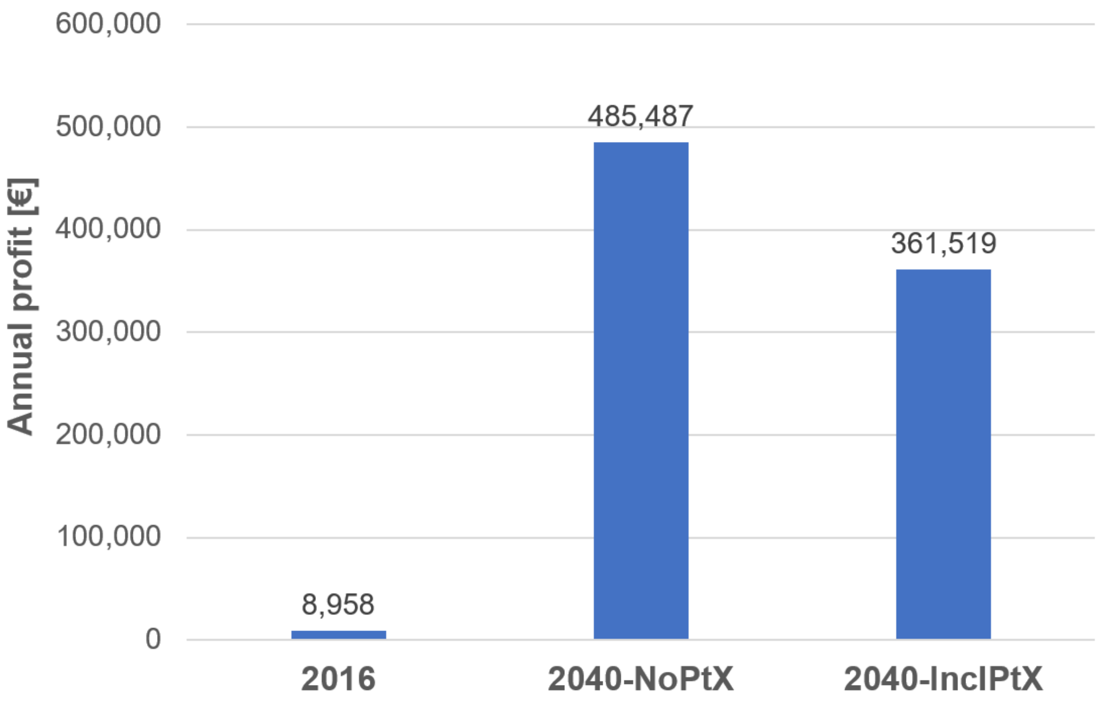

Figure 12 Annual profit of CHEST for participation in the Danish spot electricity market for spot market profiles of 2016 and 2040.

Figure 13 shows the annual profit for the participation of CHEST in both the spot electricity and tertiary regulation market. The annual profit for the spot market profile of 2016 is in this case much higher compared to Figure 12, which means that most of the profit is generated in the regulation market. For the 2040 spot electricity market profiles, only a slight improvement in the profit by activity also on the regulation market suggests that most of the profit is generated in the spot market. However, it is worth noticing that the price profile of the tertiary regulation market from 2016 was used since the price level at the regulation markets in 2040 is unknown. Anyway, even with the regulation market price profile of 2016 used here, the regulation market does also play an important role in 2040 as can be seen with the increase of the profit numbers between Figure 12 and Figure 13. Probably, the increased need for electrical energy storage in the future will also lead to increased regulation volumes and electricity prices in the regulation market. So, the expectation here is that the profit should even be higher in 2040.

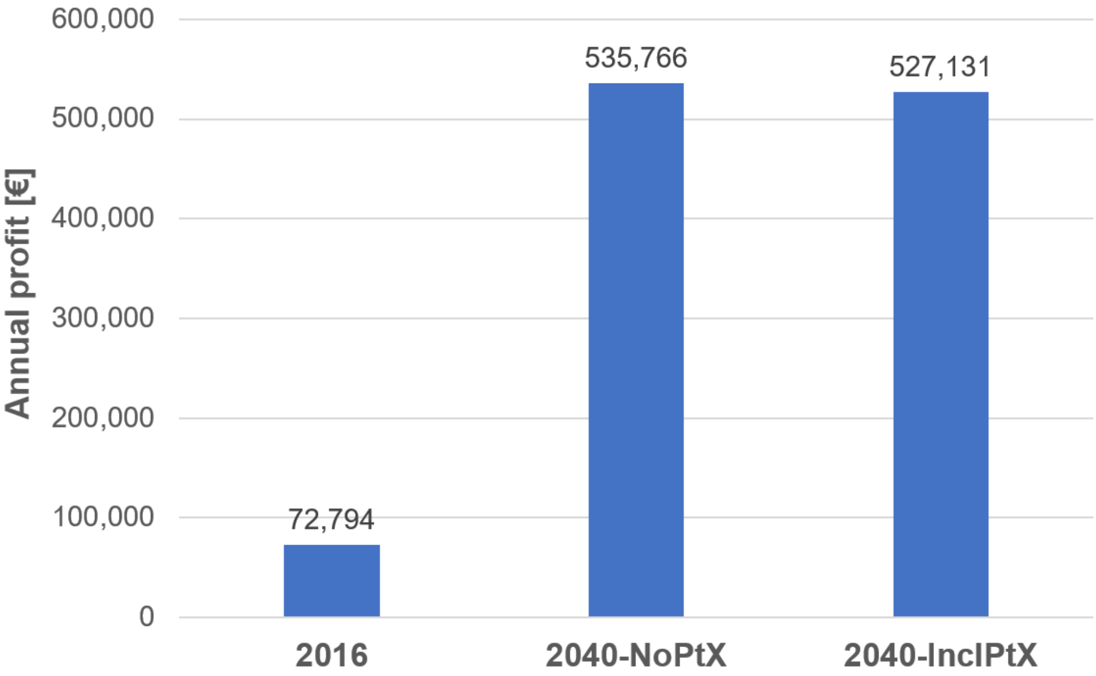

Figure 13 Annual profit of CHEST for participation in the Danish spot electricity and tertiary regulation market for spot market profiles of 2016 and 2040.

6.4. Conclusions

This additional analysis on the economic assessment of the Aalborg case study clearly shows a considerable improvement of the profit of a grid-connected CHEST system participating in the spot electricity market in the year 2040. The higher level and fluctuation of the electricity prices in 2040 increase the operation times of the HP and of the ORC due to a higher demand for charging and discharging and this eventually increases the annual profit.

However, the key message for the business case based on arbitrage is that the annual profit due to selling electricity at favorable prices is still quite low (nearly 200 times less) compared to the currently expected investment costs of several tens of million €. This brings the conclusion that the investment costs of the CHEST system, especially of the PCM storage have to be decreased significantly. Furthermore, the taxation on electrical energy storage and the O&M costs of the CHEST system need to be lowered to increase the profitability of the CHEST system for the business case of the participation in the electricity markets considered here.