CHESTER

Compressed Heat Energy
Storage for Energy
from Renewable sources

D6.6 Market replicability potential

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Nomenclature

CAES	Compressed air energy storage
CAPEX	Capital expenditure
CHEST	Compressed heat energy storage
CHESTER	Compressed heat energy storage for energy from renewable sources
CHP	Combined heat and power
COP	Coefficient of performance
DH	District heating
DSO	Distribution system operator
EEP	Excess electricity production
EES	Electric energy storage
EU	European union
HFCSS	Hydrogen fuel cell storage system
HP	Heat pump
HT	High temperature
HT-TES	High temperature thermal energy storage
IRR	Internal rate of return
LT	Low temperature
O&M	Operation and maintenance
OPEX	Operational expenditure
ORC	Organic Rankine cycle
P2P	Power-to-power
PCM	Phase change material
PHES	Pumped hydro energy storage
PV	Photovoltaic
PtX	Power-to-X
TES	Thermal energy storage
TSO	Transmission system operator

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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.

The work documented in the present document builds on work documented in a preceeding report: *Market technological potential* [1]. The preceeding work includes an energy system model, and a procedure for modellling the operation of CHEST in a national scale energy system. Here, a number of scenarios are analysed from a technical perspective providing some initial conclusions and indications of where to identify a possible economic potential.

The aim in the current work is to assess the economic potential in integrating CHEST systems on a high and overall system level, corresponding to national and European level. This will enable general conclusions of the market and replicability potential for future introduction and integration of CHEST systems at a larger scale. This is intended to supplement case studies and business models on a local and facility scale level.

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* [2]. 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 [2]. 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

In some cases it will only be relevant to consider direct electricity storage, and the technologies in this segment can be categorized according to different technological characteristics and their ability to participate in different market. In Figure 1 some of the most common electricity storage options are compared according their discharge time and power rating. Through the simulations and assessments in WP4 and WP6 the services that could be provided by CHEST have been analyzed and it has been concluded that CHEST will mainly address the services provided by the high power (>10MW) and discharge time (>1 h). For these services the number of existing alternatives is very reduced. In this range pumped hydro energy storage (PHES), compressed air energy storage (CAES) and hydrogen fuel cell storage system (HFCSS) are available, and to some extent also Batteries. Where PHES and CAES are limited by physical and geological constraints, HFCSS is the only directly comparable competitor on large scale applications.

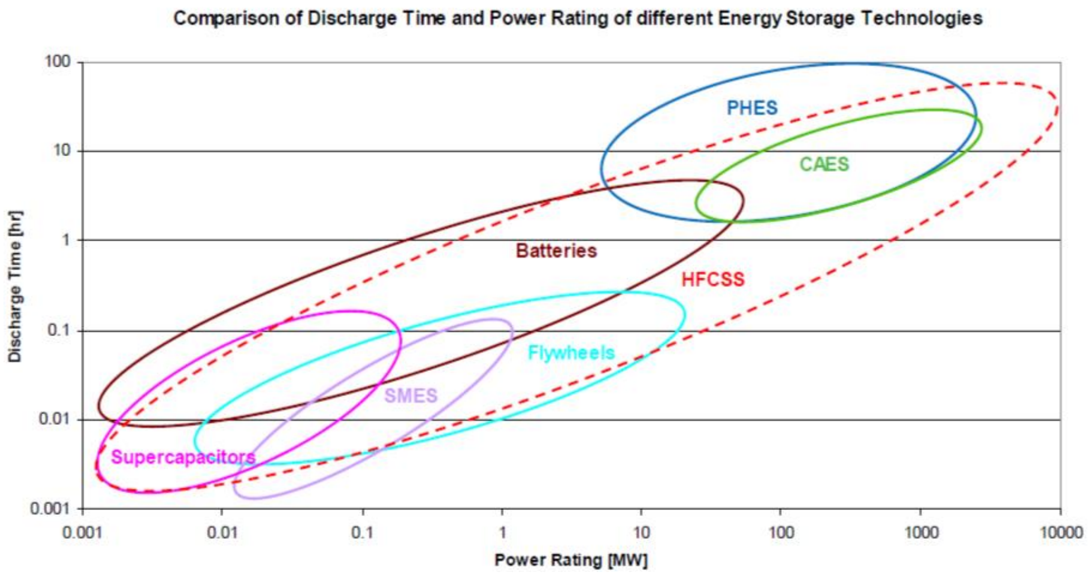

Figure 1: Different energy storage technologies depending on the discharge time and power rating.

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 investments costs, so this can change the relative competitive situation as well.

1.2.2. Framework conditions and market trends

In the CHESTER publication *Business cases definition and baseline for business models* [3], 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 actor, 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 CO_2 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 in the agenda of policy makers in different countries.

A number of more specific barriers to the growth of CHEST and electricity storage in general have been identified in [4]. 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. Technical market potential

In the abovementioned report of the CHESTER project, *Market technological potential* [1], it is assessed how CHEST systems can potentially contribute technically to the energy supply in different scenarios. It is found that there is a technical potential for CHEST in a future energy system context with large shares of renewable electricity production. The technical potential is determined by a reduction of the indicator *total primary energy supply*, which indicates an increase in the total energy system efficiency, by integrating larger amounts of fluctuating renewables. The potential is found in an integration where the CHEST only operates on the electricity markets (Electricity-only), but an even larger potential in system integrations where CHEST operates both on the electricity market and an electrified heat supply system (Heat-exchange). The heat system is in that context assumed to be a district heating system, but could as well be an integration with an industrial process system or similar. In the mentioned report CHEST is compared to a Lithium-ion battery, on the technical performance of the electricity-only integration which shows is less effective, due to the lower power-to-power ratio of the CHEST. However, the Heat-exchange integration performs better than the corresponding Lithium-ion battery system, despite the lower power-to-power ratio, because the additional benefit from the heat supply system.

1.3. Content and structure of the document

The document is structured in four main chapters, where Chapter 1 is the introduction to the report. Chapter 2 Materials and methods presents the methods, approaches and assumption for the conducted analyses. Chapter 3 Results presents the main results of the analyses which lead to the conclusions. In Chapter 4, the analyses and results are discussed and the main conclusions are drawn based on that. Chapter 5 holds a list of references for the report.

2. Methods

2.1. Summary of preceding methodology

The current study builds on the preceeding study documented in [1]. The analysis in this 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 preceeding study does not consider economic aspects, but merely the technical aspects of the integration of CHEST in large-scale systems.

The screening of the capacity potential, the first analysis part, aims to identify the scale of the technical market in which CHEST may be feasible. This is done using energy system models of the six EU member states that are represented in the CHESTER consortium: Germany, Italy, Spain, Belgium, the Netherlands and Denmark for the year of 2050, where large renewable energy penetration is to be present. The screening assesses the long-term maximum technical potential, in terms of installed capacity, in an electricity-only integration as well as in an electricity and heat-integration of CHEST. The assessment relates to specific energy system characteristics of the countries' 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 the EU average well. 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 that were specifically developed for the purpose of this study. The energy system models include all main energy demand categories of heat, electricity, industry 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.

2.2. Considerations on the assessment of future economic market for CHEST

The future economic market for CHEST is highly relevant for analysis in this project to be able to assess the relevance of this technology. As the technology is not completely ready to be marketed today, the current market may not be a good representation of the future market in which CHEST will have to compete.

2.2.1. Uncertainties in future markets and energy prices

The future market for CHEST is not easy to predict, however, because the supplies of energy products such as natural gas, oil, biomass or electricity are subject to multiple different interests apart from the economic costs, such as environmental sustainability, geopolitical conflicts, national balance of payment or security of supply. These issues over time significantly influence the market prices for various forms of energy and its supply to the consumers, and may not be linked to the actual costs of producing the energy. Individual states may also introduce local regulations that limit certain forms of fuel, subsidise certain investments or tax certain forms of energy technology, which also affect the consumer prices and potential investment decisions, e.g. towards a CHEST system.

Given these uncertainties to the development of future market prices for energy, an analysis of the future economic market for CHEST based on energy price prediction alone will be equally uncertain.

2.2.2. Implications of the renewable energy transition

What is less uncertain and unpredictable than the energy prices is the trend towards more renewables in the form of wind and solar energy and a phase out of fossil fuels. This trend can be seen all across the EU and in many other regions of the world, and is a result of the increasing awareness of the consequences of global warming resulting from greenhouse gas emissions. In some places the trend is faster than in others, but generally it is an increasing trend all across the EU.

When the energy systems are transitioning from fossil fuel-based supply to supply based on wind and solar power, some general characteristics will apply:

- An increasing share of the total system costs will relate to investments rather than purchase of fuel
- An increasing electrification of other energy related sectors (transportation, heating, industry) will be needed to effectively utilize the wind and solar power produced
- The increase in fluctuations of the production of wind and solar power will increase the need of flexibility in dispatchable production and demand-side management

The remaining use of fossil and biomass fuels can vary depending on the state of transition, the availability of fuels and the implementation of measures to reduce demands. There will most likely remain a share of fossil and biomass fuels in the supply for several decades to come in the EU due to technical and economic challenges of converting all demands to renewable energy sources. The use of imported fuels can theoretically be completely removed by introduction of large wind and solar power production capacities, deep energy efficiency and electrification measures, along with electrolysis and the production of synthetic fuels for demands that cannot be electrified. However, the last 10-20% of the phase-out of fossil fuels is the most challenging and the most uncertain ones in terms of technological solutions.

2.2.3. Potential economic market estimation based on costs

When an energy storage solution is integrated into an energy system, it will be operated in the available markets in the given context and earn an income based on marginal price differences on buying and selling electricity and heat. These payments should reflect the value in the system and the market of consuming and producing electricity and heat at different times. The large uncertainties in the development of the prices and markets for energy, as mentioned, make this way of quantifying the value of an energy storage solution equally uncertain in the long term, and hence the potential economic market.

In this analysis, the potential economic market is based on an analysis of the total costs of the energy supply, including investments and operation costs. The benefit, or the value, of the CHEST system is quantified here using the avoided costs in the system, in terms of reduced consumption of fuel, reduced operation and maintenance and reduced investments. These benefits should be larger than the increased investment costs in the CHEST systems itself, and if so, there is a potential economic market. This does not mean that a market will necessarily occur, but an estimation of the potential for an economic market to exist. Similarly, an economic market may also emerge due to a supporting regulatory framework.

The investment costs for wind turbines, solar PV panels, heat pumps, electric vehicles, power-to-x, etc. are central in the future energy supply based on high shares of fluctuating renewables, and they constitute a significant part of the total energy system costs. In contrary to the existing energy systems, which are based on consumption of fuels and costs highly sensitive to changes in international energy market situations. In a renewable based energy system the costs are mainly investments which are known at the point of invenstment, and reduces the uncertainty of future energy supply costs. The investment costs may increase due to increases in material costs, labor costs etc., but at the same time there is a technological development, which decreases the investment costs over time. And these investment costs will generally be much less sensitive to international market situations compared to fuels.

2.3. Economic assessment of CHEST

2.3.1. General approach

The economic perspective is built on a bottum-up approach, where the technical energy system and the inherent characteristics of its components serve as the foundation. The idea is to calculate and include all relevant costs of the energy system, which might be affected by various changes in the system. By including and quantifying all relevant parts of a national energy system in the analysis, the overall impacts of the analysed system can be observed.

The economic perspective is seen from an overall view, as the possible identified costs and benefits are not linked to certain market actors or technologies, but identified as a generel potential in the given system context. Hence, the national legislation, tax structure, market regulation, possible support schemes etc. are not included in the analysis, but merely the actual costs related to material and labor costs in connection to technology investments, fuel costs and the related distribution costs and operation and maintenance as well as estimated damage costs of greenhouse gas emmissions.

The economic result is quantified as total energy system costs, and all costs related to the energy system are calculated based on the concrete model definition and the simulation of one year of operation. This is further elaborated in Section 2.3.2.

The approach enables an analysis that is not bound to the current market conditions, regulatory framework or political environment, but provides more generally applicable conclusions regarding the analysed type of energy system, here represented by the German energy system. An identified economic potential related to a certain technology may or may not be reflected in a positive business case in the current market conditions. This approach is even more relevant and important when looking at a long-term future energy system context, where the uncertainties are more and larger in scale than on the short term. The electricity market is an example of a set of market conditions that will likely change in a 2050 perspective, so if analyses are bound to this market design, they may be difficult to interpret if the electricity market design is fundamentally changed.

2.3.2. General economic assumptions

The general costs are adopted from cost reviews for technology and fuel costs for the EU, projected for 2050, from the Heat Roadmap Europe project. These include investment costs for the main categories of energy system production, conversion, storage and other infrastructure components documented in [5] (see Table 1). Generally, these costs will not influence the potential for CHEST, as most of these technologies will remain with a constant capacity in the different analyses.

Table 1: List of specific selected key investment costs included in the model.

Parameter	Unit	Value
Electricity supply		
Onshore wind	M€/MW-e	0.91
Off-shore wind	M€/MW-e	1.47
Solar PV	M€/MW-e	0.70
Geothermal power	M€/MW-e	3.94
Power plant (thermal)	M€/MW-e	1.26
Fuel and power-to-X		
Electrolysis for fuel production	M€/MW-e	0.25
Biomass gasification	M€/MW	0.42
Hydrogenation, liquid fuel	M€/MW	0.55
Carbon recycling	€/t CO_2/year	1.50
Individual heating supply		
Fuel boiler	k€/unit	3.36
Heat pumps	k€/unit	4.78
Electric heating	k€/unit	2.32
Solar thermal	€/MWh	1,226
District heating supply		
Fuel boiler	M€/MW-th	0.1
CHP plant	M€/MW-e	0.80
Waste incineration CHP	M€/TWh/year	316
Heat pumps	M€/MW-e	2.42
Thermal storage	M€/GWh	2.96

Future fuel prices are analysed and documented in [6], which is used in the basic scenario. In addition, the fuel prices are assessed in a sensitivity analysis. The applied costs of the reference scenario are presented in Table 2.

Table 2: Overview of applied fuel and fuel handling cost assumptions for Germany in 2050.

[€/GJ]		Coal	Oil	Gas	Biomass
Net fuel price		5	24	37	19
Fuel handling costs	Central power plant	-	0.26	0.41	1.19
	Industry and CHP	-	-	2.05	1.19
	Households	-	2.08	3.15	2.98
	Transport, road and rail	-	2.08	-	1.19
	Transport, aviation	-	0.48	-	-
	Fuel conversion plant	-	-	-	1.19

The economic results are quantified in total energy system costs, which include:

- Investment cost annualized over the technical lifetime of each technology category using an discount rate of 3% p.a..

- Fixed and variable operation and maintenance cost of the assumed technology and production mix in the given model and its simulation of a year's operation.
- Energy purchase costs, including fossil fuels, biomass, waste and electricity exchange cost.
- Costs of greenhouse gas emissions and the effects of climate changes, measured proportional to CO_2-emissions of fossil fuels.

The costs are compared as "Change in total energy system cost" and divided into CAPEX and OPEX where relevant to illustrate the impact of the different analyses. The total energy system costs include many components that are not affected by the introduction of a CHEST system.

2.3.3. Specific CHEST related costs

The main cost assumptions for the CHEST unit components are shown in Table 3. Two scenarios are included to describe the current cost level and a possible and realistically achievable future investment cost level for the technology. The timing of the achievement of the future cost level is not defined, but describes the realistic cost level which can be achieved with some further development and upscaling of both component sizes and number of components produced.

The costs were derived during a process in the CHESTER project, in which various sources were compared for current and future costs for the different components of the technology. This has been combined and supported by expert knowledge from the consortium partners who were involved in the development of the prototype and are up-to-date on the research in this field.

Table 3: Specific cost assumptions for the main CHEST components, in a current and a future cost scenario.

		Current	**Future**
CAPEX			
HP	€/kW-th	350	250
ORC	€/kW-el	1000	850
TES	€/kWh-th	100	50
OPEX			
HP	€/MWh-el	5	5
ORC	€/MWh-el	10	10
TES	€/MWh-th	5	5
Lifetime			
HP	years	25	25
ORC	years	25	25
TES	years	40	40

2.4. Scenario analysis

To analyse the economic potential for CHEST in different markets, some different scenarios for the integration of CHEST were applied. The technical foundation for these scenarios was developed as a part of the previous study documented in [1]. A principal diagram of a CHEST possible integration can be seen in Figure 2. The economic assumptions presented in Section 2.3 have been applied to the technical model. There are three basic scenarios around which the analyses are structured:

1. **Reference scenarios** – No integration of CHEST.
2. **CHEST Electricity-only** – CHEST is integrated where only the electricity side is utilized. The heat source is assumed to be freely available from an industry or similar, and the excess heat is led to a heat sink by dissipation into the environment. Hence, no expences nor income from the operation of the heat side.
3. **CHEST Heat-exchange** – CHEST is integrated with utilization of the electricity side as well as the thermal side. The thermal side can be exchanged with a district heating system or an industrial complex with excess heat and heat demands within the same proximity. The heat consumption of the HP will be connected to a cost in the system it is drawn from, and the heat output of the ORC can replace some costs when it is delivered, and thereby possibly generate a revenue.

The CHEST scenarios (2 and 3) are identical to the Reference scenario except for the integration of CHEST.

In [1], there are two different scenarios for the Heat-exchange scenario: one where the heat supply is covered mainly using fuel based production units (CHP and fuel boilers) and one where the heat supply is covered using electrified sources (heat pumps). The technical analysis showed that the fuel based systems interact with a CHEST system in a counter-productive way, where the CHP and the CHEST compete by preferring to operate in the same situations when they are in the same system. However, in the electrified system, the heat pump and CHEST supplement each other by preferring to operate at different times, and thereby improve the overall system efficiency. Based on this result, it was chosen to continue the economic analysis only with the electrified Heat-exchange scenario in the present study.

In the previous study, the CHEST Heat-exchange scenario is referred to as "District heating exchange", however since the publication of that report [1], it has been found that industrial complexes or similar can potentially also be a part of the Heat-exchange, and not just district heating systems. Therefore, the name of the scenario has been adjusted here. The technical interaction is modelled in the same way, so it does not make a difference to the modelling.

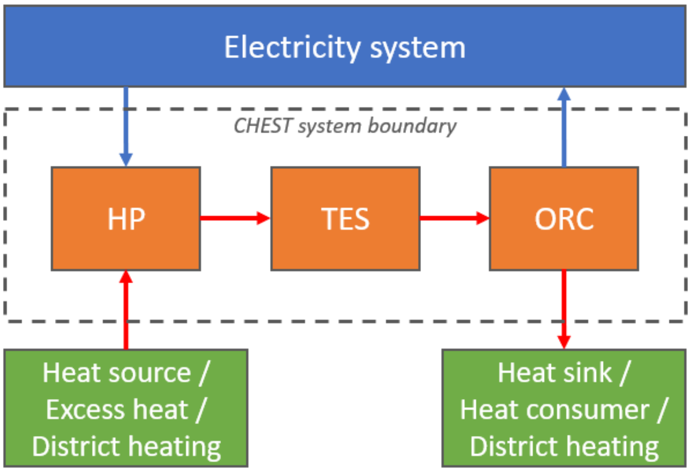

Figure 2: Principal diagram of CHEST system and components and its interaction with the electricity system and heat sources and heat sink.

The energy system of Germany projected for 2050 is used as a reference, to be able to make a better analysis of the results of introducing CHEST. This enables a more qualified assessment of the quantitative potential for CHEST in a future context and which role it can play in an energy system with a high penetration of renewables. To read more about the setup of the reference model, see [1].

2.5. 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 [7]. 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 the regional or country level. [8]

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 3). 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. In Figure 3, 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 that converts electricity into high-temperature heat.

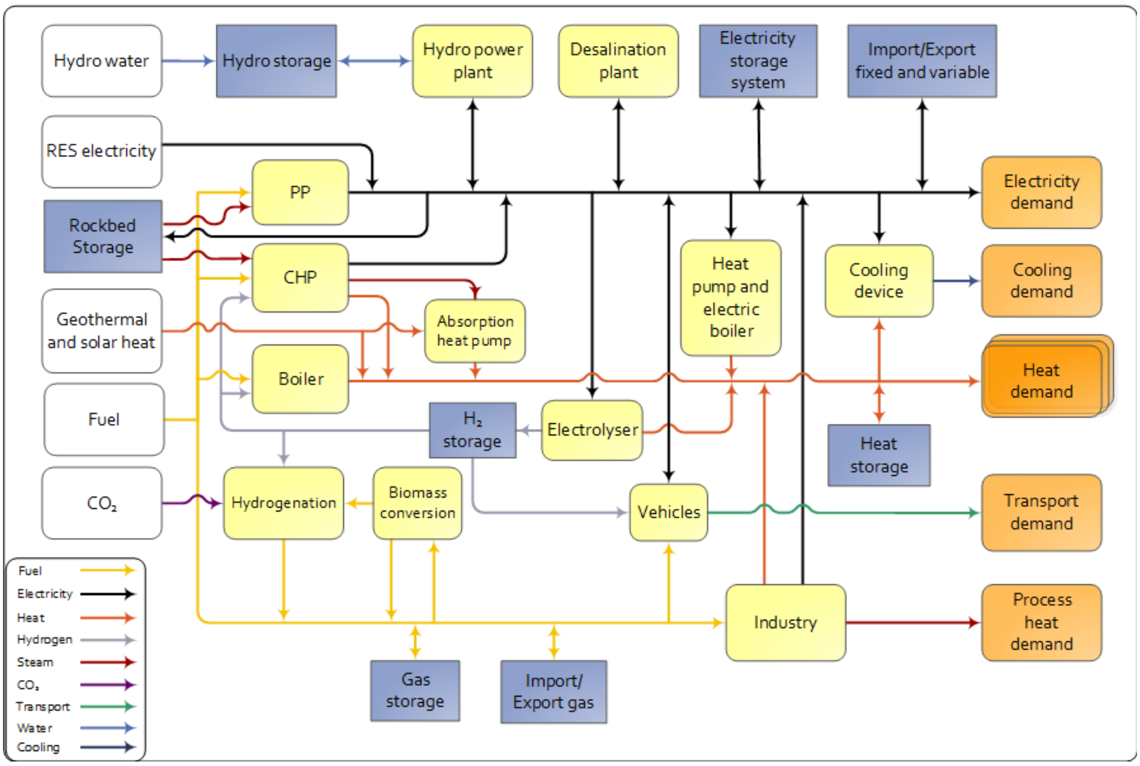

Figure 3 Overview of resources (white), conversion (yellow), storage (blue), supply infrastructure (arrows) and demands (orange) modelled in EnergyPLAN.

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 control of how storages are charged and discharged each hour when these are operated as a part of the overall energy system.

2.6. Analysis procedure

The analysis procedure is divided into four steps, where each of them provides an insight into the economic market potential of CHEST and the sensitivity of it. The analyses presented uses inputs introduced in the preceeding sections.

2.6.1. Step 1: Economic capacity optimization

The basic scenarios have previously been analysed from a technical point of view without consideration of the investment and operation costs of the components. The initial storage capacities are defined to capture the technological potential of the technology rather than the economic potential. In this step, the costs are taken into account as well and the capacities of the different storage components are varied in a range of simulations to reach a combination that is closer to the optimal situation.

First, the capacities of the heat pump and the ORC are varied so that the ratio between the capacities of the two changes, but keeping the thermal storage capacity fixed. This identifies at which ratio between heat pump and ORC capacity the optimal economic result can be achieved. Secondly, the thermal storage capacity is varied with fixed capacities of heat pump and ORC in the ratio resulting from the first part of the procedure. This gives an indication of which combination between capacities of the three different components will likely give the best economic result.

Finally, once the CHEST system with the identified ratios between the three components is set, the energy system model is scaled to identify two different points to describe the economic market potential:

- The economically optimal installed capacity of CHEST, where the total energy system costs are at the lowest possible level.
- The maximum installed capacity of CHEST, with a net-zero economic result, where the installed capacity is largest possible without generating an economic deficit.

2.6.2. Step 2: Investment cost analysis

In the second step, the sensitivity of the results to the investment cost scenarios of the CHEST, shown in Table 3, are analysed. The main purpose of this is to assess the influence of the future development in the investment costs of the components of the analysed technologies and the general economic feasibility of integrating a CHEST storage system.

After calculating the economic cost in the two given investment cost scenarios, a break-even cost level is derived by adjusting the cost proportionally to the correlation between the points of the two cost scenarios, to a level where the savings equal the capital costs. At this point, the corresponding payback period is equal to the average lifetime of the total system. This indicates a threshold level for how the investment costs need to develop to be able to have a likely feasible situation.

2.6.3. Step 3: Fuel price variations

Similarly to the assessment of sensitivity to changes in the investment costs, the scenarios are also assessed for their feasibility under different fuel price assumptions. This assessment influences the OPEX of the overall energy system and hence the potential savings that CHEST can generate. The fuel prices often vary greatly, and can be connected to international politically significant events, which are almost impossible to predict the result of in terms of energy price fluctuations. See examples of recent concrete market prices of natural gas and wood pellets in Figure 4 and Figure 5, respectively. This is to provide an understanding of how sensitive the different scenarios are to the general fuel prices.

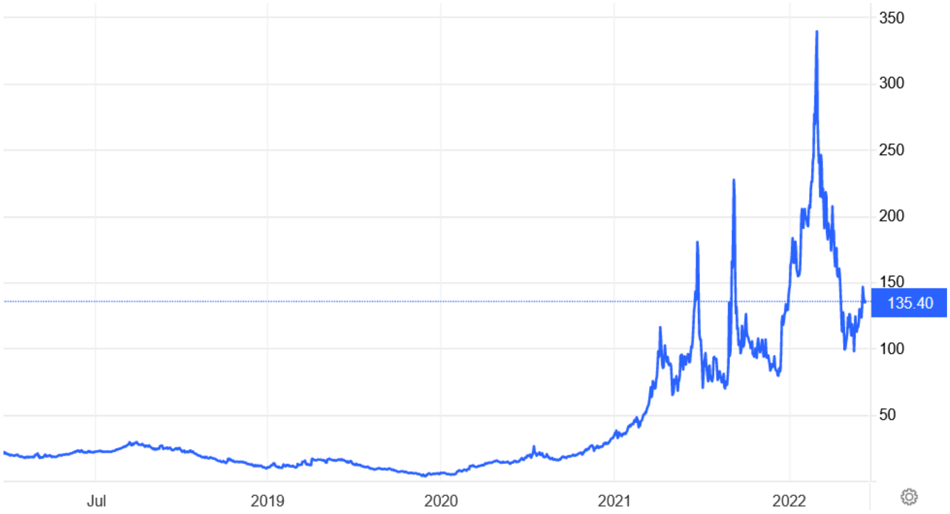

Figure 4 Natural gas market price development - Example of the Dutch TTF trading point [9]

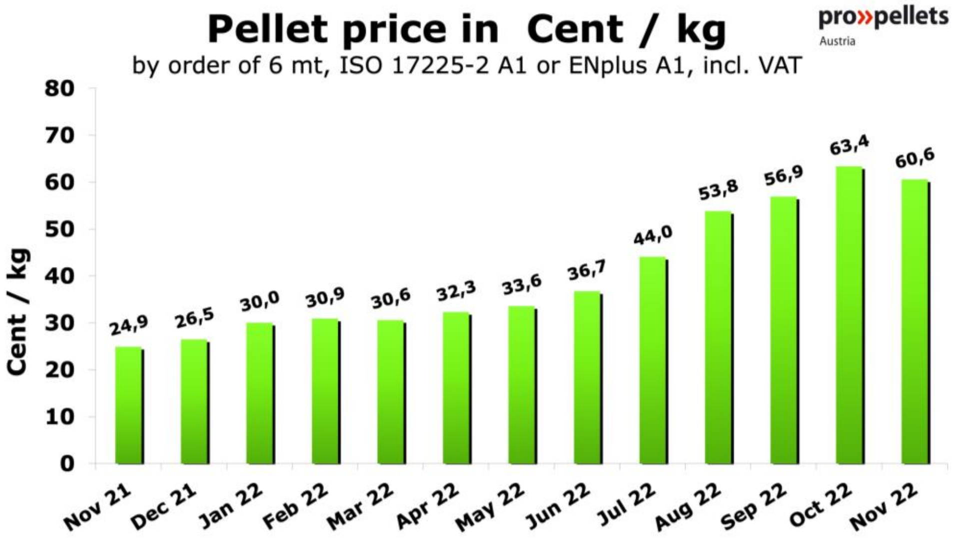

Figure 5 Wood pellet market price development - Example of ProPellets Austria historical prices [10]

The specific applied fuel costs in the sensitivity analysis are seen in Table 4. The fuel prices assumed in the sensitivity analysis are approximated from historical values of the near past. In the table, the approximate times are indicated. It should be noticed that the reference price level is high compared to the prices of just a few years ago.

Table 4 Fuel price variations in the sensitivity analyses with reference to approximate point in time where the prices have occured.

(€/GJ)	Reference point	Biomass	Natural gas
High	Mid 2022	36	74
Rerefence	Late 2021	19	37
Low	Early 2021	9	18

2.6.4. Step 4: Total economic market assesment

In the last and fourth step, to assess the total economic market potential for the EU-market, the results are extrapolated from the reference case to the EU-market based on the current primary energy supply (see Table 5). This gives an indication of the scale of the economic potential for the EU in total, in economic terms as well as in terms of resulting primary energy supply, of introducing CHEST. The results are compared between the different results for the technical market potential as well as for the feasible economic market and optimal economic market.

Table 5: Primary energy supply of the EU27 and Germany in 2020.

	Primary energy supply		Source
EU27	54,7	EJ	[11]
Germany	14,1	EJ	[12]
Germany share of EU	23.5	%	-

3. Results

The results are presented according to the four steps of the analysis, as introduced in Chapter 2, where key figures are given and explained. In the following Chapter 4, the results and their implications are discussed further.

3.1. Capacities analysis

The analysis of the capacities of the CHEST system is analysed in three consecutive parts, where each provides an input to the assessment of the optimal capacities of the CHEST system in a large scale energy system application. The three parts are:

1. Analysis of the economically optimal HP/ORC ratio with fixed TES capacity
2. Analysis of the optimal TES capacity with the HP/ORC ratio fixed
3. Analysis of the overall CHEST capacity with the identified HP/ORC/TES capacity fixed

3.1.1. HP/ORC ratio

The first analysis evaluates the economic optimal capacity combination between heat pump and ORC. The economic results of the analysis can be seen in Figure 6. Each of the four blue points on the graph illustrated the result of an analysis and the overall economic result of it. In each of the four points, there are 10 GW-e capacity installed combined between HP and ORC. This means that where the HP/ORC ratio is 1, there is 5 GW-e heat pump capacity and 5 GW-e ORC capacity assumed. In all the cases, a fixed TES capacity of 50 GWh are assumed. At the ratio 4, there is 8 GW-e capacity of heat pump and 2 GW-e capacity of ORC. It can be seen that the point with a ratio of 4 generates the lowest total energy system cost of the analysed points, and thereby identifying the optimal combination under the given assumptions.

3.1.2. Thermal storage capacity compared to HP/ORC ratio

This second part analysis uses the same procedure, but here it is the capacity of the thermal energy storage in relation to the heat pump and ORC ratio that is in focus. The results of this can be seen in Figure 7. Here, the HP/ORC ratio of 4 identified above is kept constant, using the values of 8 GW-e capacity of the heat pump and 2 GW-e on the ORC, and only the thermal storage capacity is varied. The results show that the thermal storage capacity of 50 GWh in combination with the mentioned HP and ORC capacities reaches the lowest cost level identified of the analysed cases.

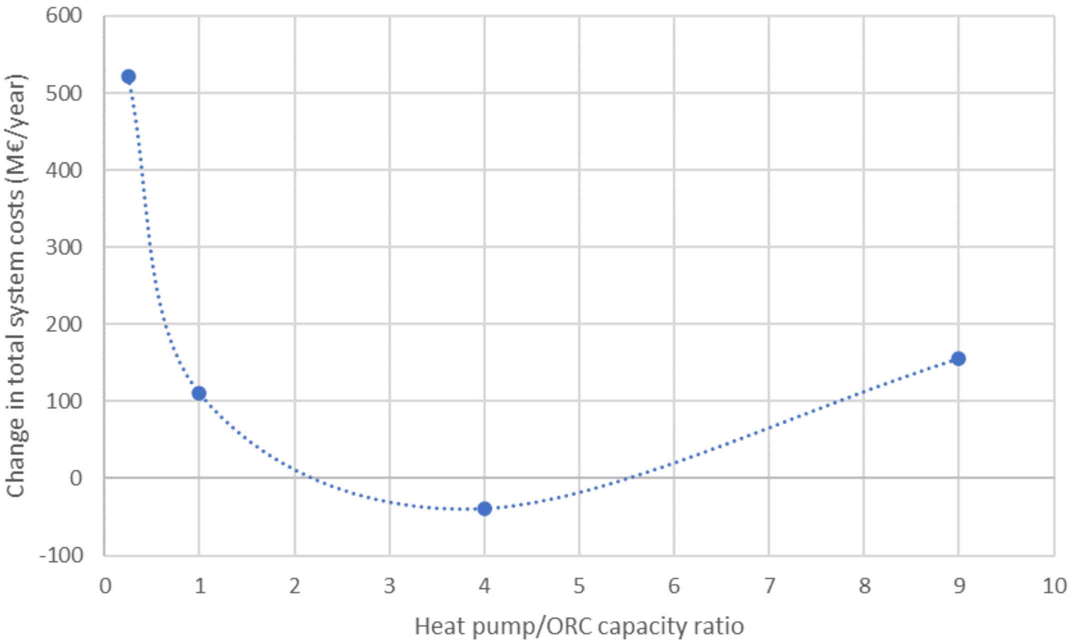

Figure 6: Total system costs as a function of HP/ORC capacity ratio. The optimal point is the combination of 8 GW-electric capacity of the heat pump and 2 GW-electric capacity of the ORC. The thermal energy storage capacity is fixed at 50 GWh in this graph.

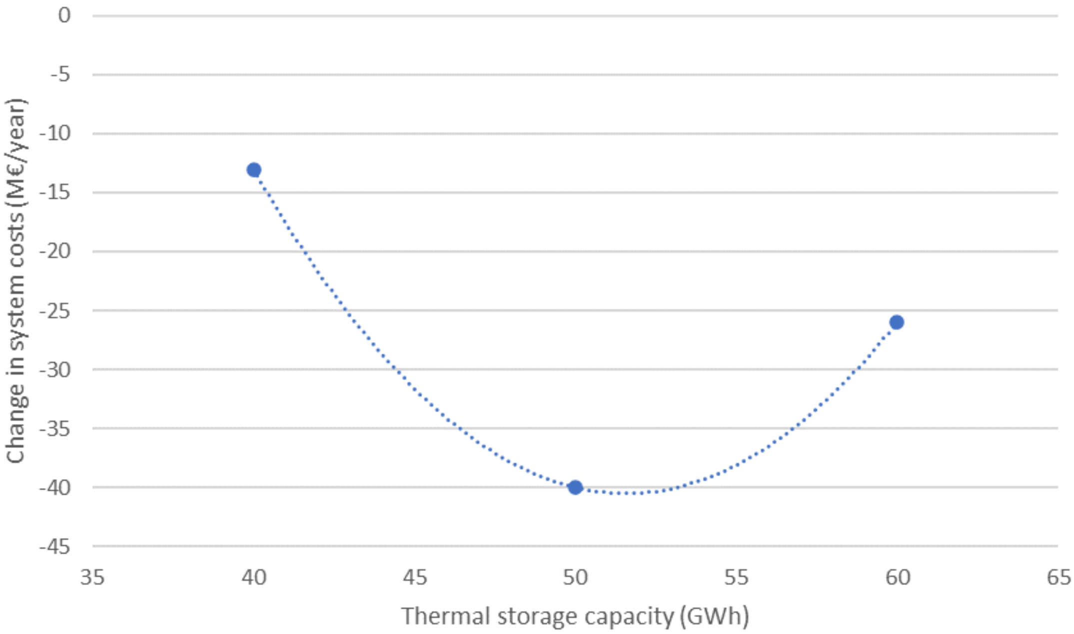

Figure 7: Total system costs as a function of thermal energy storage capacity. The heat pump capacity is 8 GW-electric and the ORC capacity is 2 GW-electric.

In the results of the first two parts of the analysis, an optimal point within the analysed combinations is identified. This is not a fixed point, though. Firstly it should be seen as an approximation of a range, or an order of magnitude, in which the optimal combination lies. The optimum may also vary in time as the mix of electricity production changes, as well as the demands for electricity. However, given the assumptions for this analysis, the general ratio between the three main components can be reduced to the figures presented in Table 6. The ratio is not necessarily the optimal combination in every single application of a CHEST system, but this is on the aggregated level.

Table 6: Economic optimum capacity ratio of main components of CHEST systems on a national aggregated level.

Component	Value	Unit
Heat pump	4	GW-e
ORC	1	GW-e
Thermal storage	25	GWh

3.1.3. General economic market potential

To identify the general economic market potential, the ratio identified in the preceding analysis part has been applied and scaled to different capacities of CHEST, where the identified ratio is kept constant. The different CHEST capacities each result in an economic result, which in Figure 8 is presented in terms of change in total energy system costs. The calculations are made for both the Electricity-only integration and the Heat-exchange integration, identified by the different colors in the graph.

For the Electricity-only integration case, the optimal of the analysed cases, in terms of total economic costs, is the CHEST capacity equivalent to 8 GW-e of the heat pump, resulting in a reduction in total costs of 40 M€/year in the reference model. The maximum economic potential is identified to be around 17 GW-e capacity, under the given assumptions. For the Heat-exchange integration case, the economic optimum lies at a lower installed capacity, between 1.5 and 2 GW-e capacity. But the corresponding economic reduction in costs is higher, here about 90 M€/year. Similar to the optimal potential capacity, the maximum potential capacity is also lower than the Electricity-only case, around 3 GW-e.

In Table 7 a summary of the identified potential economic market in terms of capacities and economy is presented. Here it can be seen how the Heat-exchange integration provides a better economy, but lower capacity, and thereby market volume, than the Electricity-only integration.

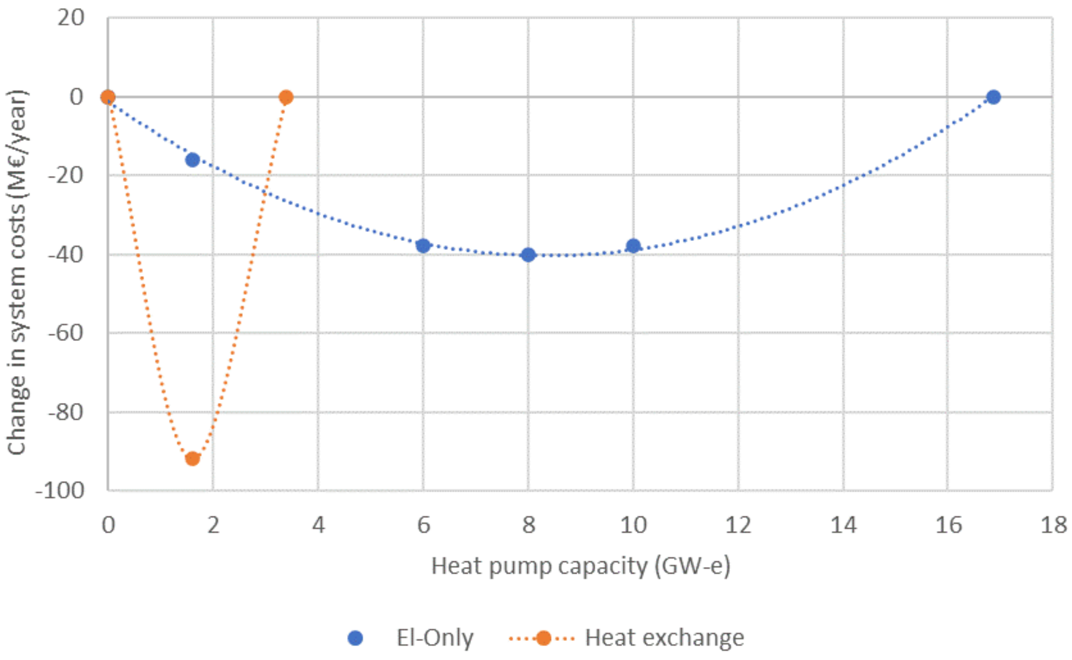

Figure 8: Total energy system costs in the Electricity-only scenario and the Heat-exchange scenario, as a function of the total installed capacity of CHEST. In this situation, the ratios between the component capacities are fixed to: Heat pump 4 GW-electric, ORC 2 GW-electric and thermal energy storage capacity 25 GWh-electric charge (corresponding to 100 GWh-thermal storage) and scaled proportionally.

Table 7: Summary of results for the economically optimal market potential and the maximum market potential for the Electricity-only integration and the Heat-exchange integration, for the reference model for Germany.

	Electricity-only integration		**Heat-exchange integration**	
	Optimal potential	Maximum potential	Optimal potential	Maximum potential
Capacity (GW-e)	8,0	16,9	1,6	3,4
Economic benefit (M€/year)	40	0	92	0

3.2. Investment cost analysis

In this section the results of the investment cost analysis are presented. First, the shares of the three main components in the total costs are illustrated. Afterwards, the results of the sensitivity analysis is presented. In this part it is only the investment costs that changed, hence the operation of the CHEST system remains the same. The analysis considers two cost scenarios: Current and Future, as introduced previously (see Table 3), and identifies a break-even investment costs level. The analysis is conducted for Electricity-only integration and Heat-exchange integration.

In Figure 9, the resulting composition of total investment costs for the main CHEST components is shown. It can be seen that the ORC makes up for 10% and the HP and TES approximately equally divide the remaining 90% of the total annualized investment costs. The ORC is much lower in costs than the HP, mainly because the installed capacity is lower. If one or more of the components would reduce in costs, the economic optimum balance in the capacity ratio might shift as well.

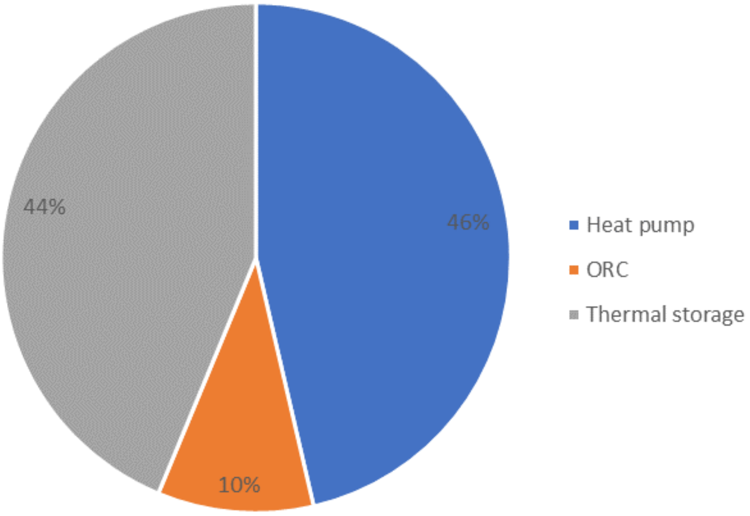

Figure 9: Composition of total annualized investment costs for a CHEST system using the resulting capacity ratio between HP, ORC and TES.

In Table 8, the results for Electricity-only integration are shown. It can be seen that the savings for operation stay the same in alle cases. However, the CHEST investment costs differ due to the different investment cost assumptions. The change results in a net saving in each of the cases, compared to the reference (Future costs), with a positive annual saving. However, in the case of Current costs, the investment costs will be significantly larger than the potential savings, which indicates that the investment will not be paid back. This can also be seen in the internal rate of return (IRR) of 0% and the payback period that is larger than the average technical lifetime of the CHEST components of 30 years. The average lifetime in this connection is used with the total costs in which the investment costs are quantified as annualized costs, which level out the differences in the technical lifetime of the three main components, HP, ORC and TES.

The break even costs level in Electricity-only integration is relatively close to the future costs. Here, the IRR is 3%, which equals the assumed discount rate of the annualized investments, and the payback period equals 30 years, which is the lifetime of the technology. It can also be seen that the savings and annual investment are identical. The fact that the future costs and the break-even costs are so close indicates that the assumed future costs will have to be achieved for the technology to be economically feasible under the given assumptions.

Table 8: Results of investment cost analysis for CHEST Electricity-only integration.

		CHEST Electricity-only (HP 8 GW-e)		
		Future costs	Current costs	Break-even costs
Saving on operation	(M€/year)	1.030	1.030	1.030
CHEST Investment	(M€/year)	990	1.623	1.030
Net saving	(M€/year)	40	-593	-
Internal rate of return	-	3%	0%	3%
Payback period	years	29	47	30

In Table 9, the corresponding results for the Heat-exchange integration are shown. It can be seen that the savings are lower than in the Electricity-only integration, but the investments are also lower. This is due to the lower overall potential for the Heat-exchange integration and lower capacities. In the Future cost case, the net saving is 92 M€/year and the IRR is 6% in this case. The savings in the Current cost case are obviously lower due to higher investment costs, but not as much lower as in the Electricity-only integration. Here, the IRR for the Current costs is 2% and the payback period is 34 years, which is close to the break-even level. This means that the needed reduction in costs compared to the current costs is low, and it is more likely that a low cost reduction can be realized than a larger one, as needed for the Electricity-only integration potential.

Table 9: Results of investment cost analysis for CHEST Heat-exchange integration.

		CHEST Heat-exchange (HP 1.6 GW-e)		
		Future costs	Current costs	Break even costs
Saving on operation	(M€/year)	291	291	291
CHEST Investment	(M€/year)	198	325	291
Net saving	(M€/year)	92	-35	-
Internal rate of return	-	6%	2%	3%
Payback period	years	20	34	30

In Table 10, the specific costs for the current and future cost assumptions are presented, together with the specific costs for the two break-even points for the Electricity-only and the Heat-exchange integration cases respectively. It can be seen that the break-even costs for the Electricity-only integration are lower than the Heat-exchange integration, and close to the future cost level. Similarly, it can be seen that the break-even costs for the Heat-exchange integration is higher, which means that an economically feasible solution can can be found in the Heat-exchange case more easily, and at a cost level close to the one of today.

Table 10: Resulting specific break even cost levels for Electricity-only and Heat-exchange integration cases.

		Current costs	**Future costs**	**Break even costs**	
				El-only	Heat-exchange
HP	M€/MW-e	350	250	256	324
ORC	M€/MW-e	1000	850	859	960
TES	M€/GWh-e	100	50	53	87

3.3. Fuel price variations

In the fuel price analysis, the focus is the sensitivity of the results to changes in fuel prices, according to the fuel price levels given in Table 4 on page 20. The fuel price is a defining factor in the savings in operation costs for the introduction of CHEST systems. Generally speaking, lower fuel prices will reduce the potential for generating an economic saving, but higher prices on the other hand will increase the potential saving and benefit of a CHEST system.

Figure 10 shows the results of the analysis for the Electricity-only integration and the three defined fuel prices levels. The main components of the changes in costs are investment and fixed O&M costs, which are identical across the different cases, because they are linked to the CHEST investment. In this, it is assumed that the investment costs will remain constant at different fuel prices levels. However, if the fuel price levels generally increase, the investment costs may also follow to some extent, but this possible effect is not included in this analysis. The savings in operation costs are related to biomass and natural gas purchase costs, due to the CHEST operation allowing more integration of renewable electricity on the national level.

It can be seen that the variable cost column increases with the higher fuel price level, which also reduces the total costs. The high fuel price level will generate a much larger benefit of the introduction of CHEST, whereas a lower fuel price will generate an increase in total costs. It can be seen that the total change in costs is close to 0 in the Reference fuel price level, which means that the economic feasibility is sensitive to reductions in fuel prices.

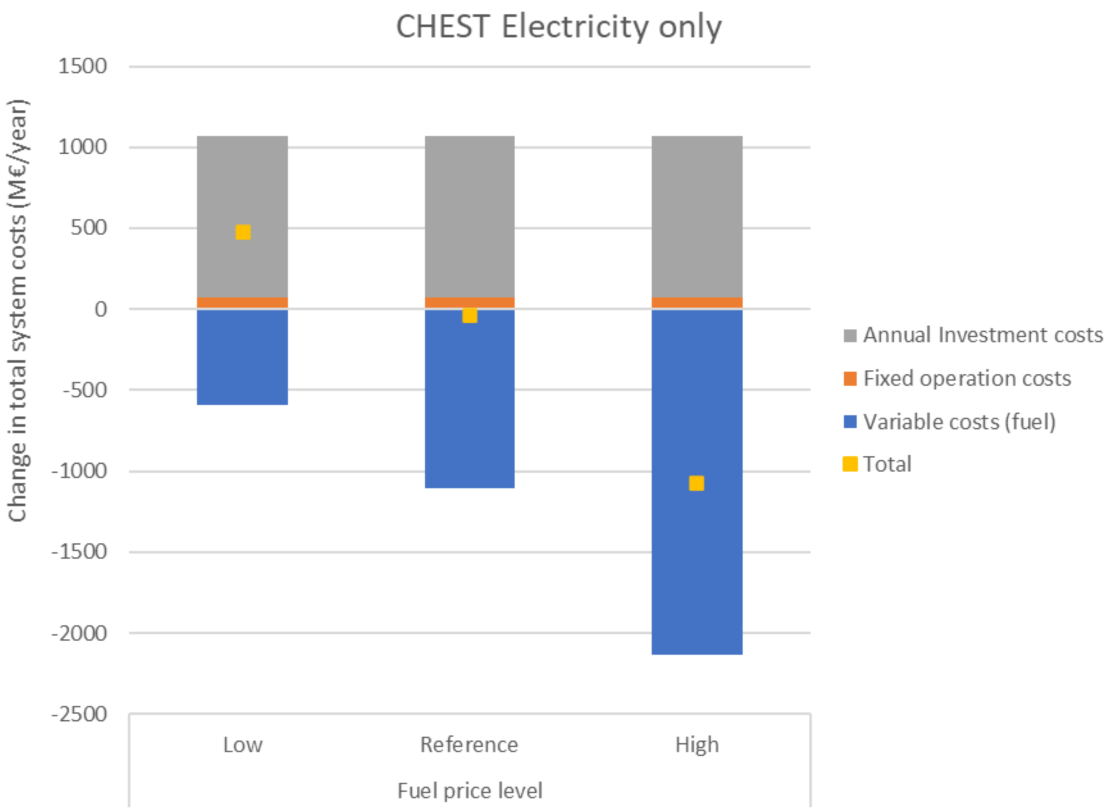

Figure 10: Results of the fuel price sensitivity analysis for the CHEST Electricity-only integration, comparing the effect of the three fuel price levels on the overall economic result.

The corresponding costs for the Heat-exchange integration are shown in Figure 11. In this case, the overall costs are lower, but the proportions are similar to the Electricity-only integration. However, the total change in system costs are lower here. In the Reference case, the margin from the total costs to 0 is substantial, which indicates that some reduction in fuel prices compared to the reference is possible and still have an economically feasible case. However, the low fuel cost level does still result in a net increase in total costs, which means that at cost levels similar to the Low case, even the Heat-exchange case may not be economically feasible.

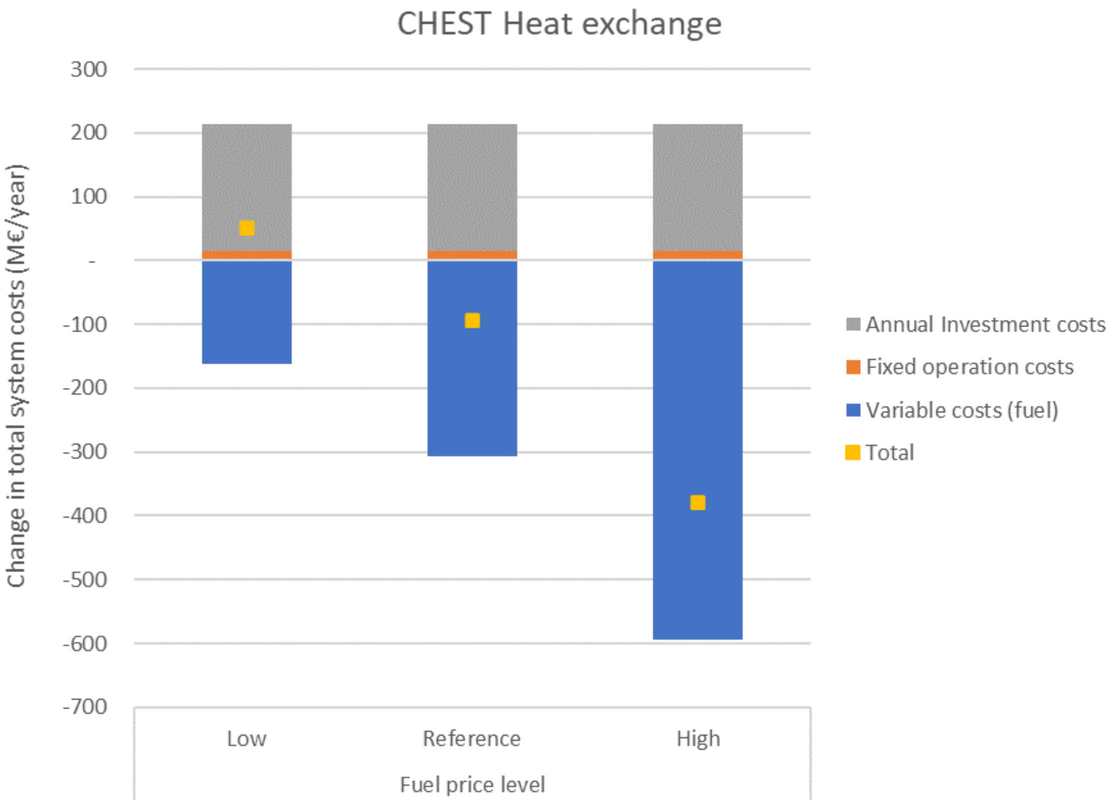

Figure 11: Results of the fuel price analysis for the CHEST Heat-exchange integration, comparing the effect of the three fuel price levels on the overall economic result.

In Table 11, the main results of the fuel price analysis are summarized and the values presented. It can be seen that the Reference fuel price level makes an economically feasible situation for both the Electricity-only and the Heat-exchange cases, but also that in both places, the Low fuel price level is not enough to make an economically feasible situation. However, the Heat-exchange integration shows to be less sensitive to fuel prices changes than the Electricity-only integration.

Table 11: Overview and comparison of results of fuel price senitivity analysis for CHEST El-only and Heat-exchange integration cases.

(M€/year)	**CHEST El-only**			**CHEST Heat-exchange**		
Fuel price level	Low	Reference	High	Low	Reference	High
Variable costs (fuel)	-590	-1.105	-2.136	-163	-306	-593
Fixed operation costs	75	75	75	15	15	15
Annual Investment costs	990	990	990	198	198	198
Total	**476**	**-40**	**-1.071**	**51**	**-92**	**-380**

3.4. Total economic market assessment

The economic market potential is defined in the first three steps of the analysis for the energy system model used in this analysis, which is a projected model of a future energy system of Germany. As presented and discussed previously, Germany is a good representation of the EU average of the heat and electricity supply, in which the CHEST is integrated. In this last step, the results for the case of Germany is extrapolated to reflect the EU scale. In addition, the results for the economic market are compared to the results of the technical market potential from the previous report of the CHESTER project potential [1].

In Figure 12, the results of the total economic market potential are presented. In the Electricity-only integration case, the optimal capacity is about 30 GW-e, where the economic benefit is about 150 M€/year in total. The maximum potential in this case is about 65 GW-e capacity. The economic optimal potential for the Heat-exchange case is only about 6 GW-e, but the economic benefit of the investment in this case is about 350 M€/year. The maximum feasible potential of the Heat-exchange integration is about 13 GW-e.

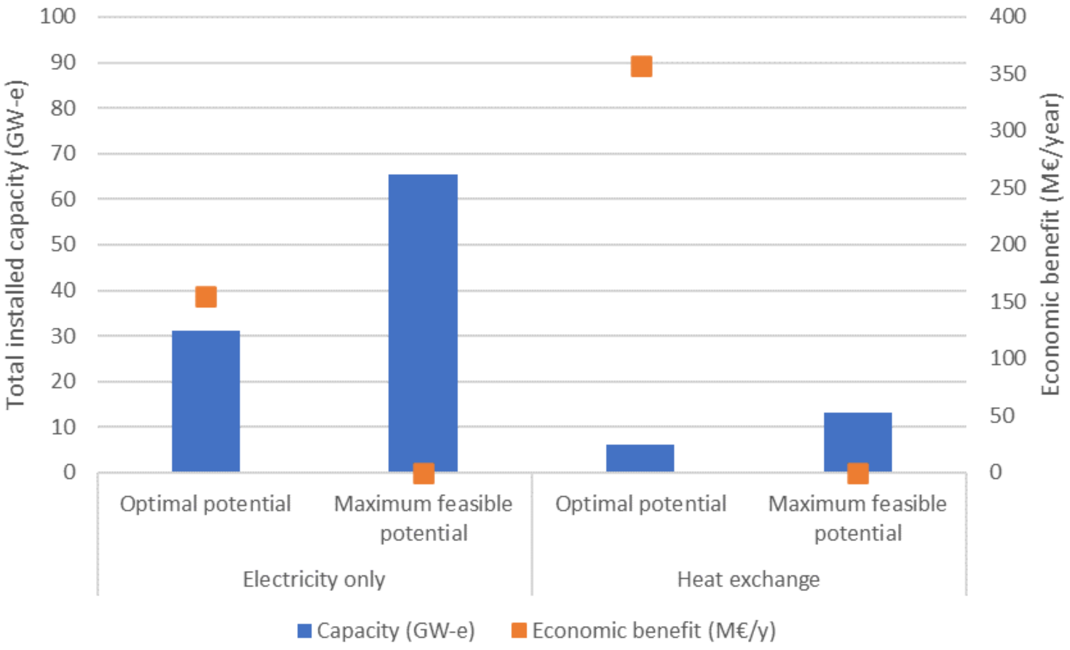

Figure 12: Resulting total market with indication of the optimal and maximum potentials, in terms of installed capacity and economic benefit, for both of the integration cases Electricity-only and Heat-exchange.

In Figure 13, the results of this analysis are compared to the corresponding results of the analysis in the preceeding report in the CHESTER project with a technical focus [1]. The results from there are extrapolated here in the same way to reflect the total markets for the EU27 area. It can be seen how the potential is narrowed down with the scope. The technical potential is largest, because here the economy is no limitation. The maximum feasible potential is lower, because the costs of the investment and the corresponding savings have to balance here, and lastly the optimal potential is the lowest of the three because the investments have to generate a profit in addition to pay back on the investment here.

The potentials for the Electricity-only integration are larger because this market covers in principle the whole electricity market. However, the Heat-exchange integration only covers applications where there is a feasible utilization of the heat side of the CHEST system, which limits the quantitative volume of the possible applications.

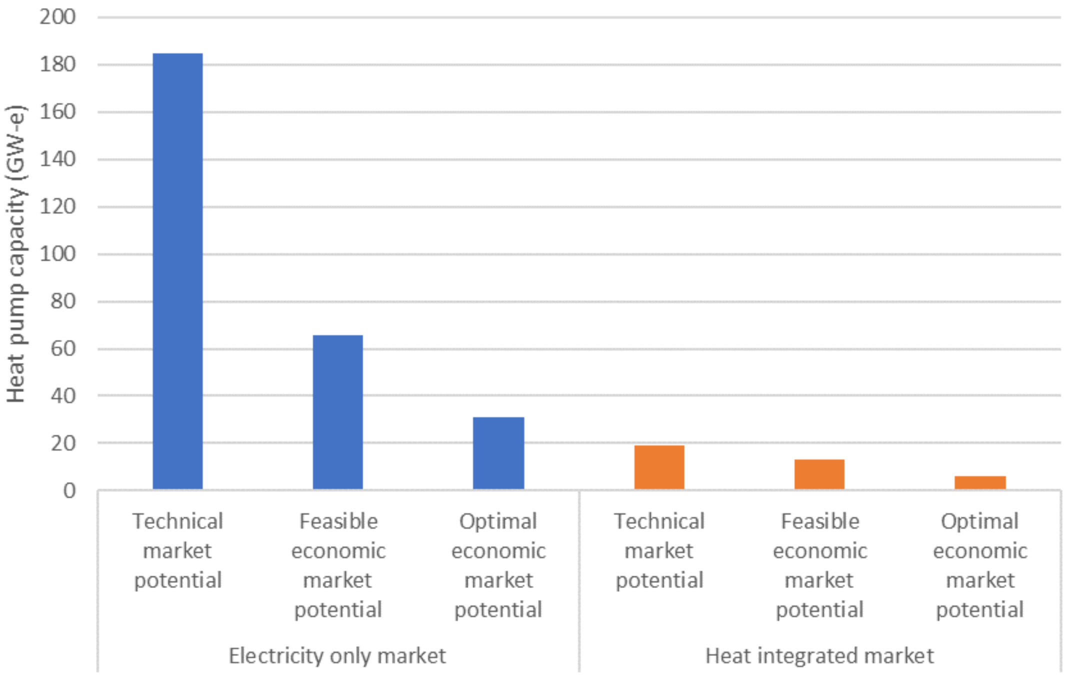

Figure 13: Potential market estimate for CHEST Electricity-only integration and Heat-exchange integration, indication Technical, Feasible economic and Optimal economic market potentials in terms of total installed capacity in the EU27.

4. Discussion and conclusions

4.1. Electricity-only and Heat-exchange markets

The two different ways of integrating CHEST in an energy system delineate two potential markets for energy storage and flexibility. The two markets are different in a number of ways, but both show that a future economic market is possible if the right boundary conditions are in place.

The Electricity-only integration of CHEST will participate in a market with other electricity storage technologies. The market for electricity-to-electricity storage shows to be a large market in terms of potential volume, and if CHEST systems show to be competitive, there may be many and large systems possible with good business cases. However, the market is also highly competitive because the product that CHEST delivers in this market can be replaced in many ways, not only by other electricity storage solutions but also other types of system flexibility. This results in lower possible revenues of an investment in CHEST, because the possible earning margins will be lower.

The Heat-exchange integration of CHEST represents a different type of market, which is more narrow and more dependent on local conditions and a customized solution, because of the interaction with heat sources and demands. These heat sources and demands, materialized in a district heating system or an industrial complex, may be different from case to case, and a detailed analysis will be needed for each individual case to assess the potential for integration of a CHEST system. On the other hand, the potential revenue connected to this way of integrating CHEST is larger because there can be a potential revenue from both the electricity and the Heat-exchange systems. At the same time, the need for integrating heat and electricity simultaneously will also limit the competition.

The two potential markets may be combined in one facility and overlap the two markets. A system that is designed for a specific heat supply system may be dimensioned larger than needed for the thermal system alone, with the purpose of participarting on the electricity-to-electricity market occasionally. In that way, it may be possible to achieve low specific costs per capacity in the Electricity-only application due to a synergy in utilizing the location more efficiently and reaching higher load factors of the overall system.

4.2. Uncertainties and sensitivities of the results

The analyses have been performed in a quantative way, resulting in specific numbers, however there are some significant uncertainties to the results, of where future investment costs and fuel prices have been assessed through a sensitivity analysis, which is discussed here.

The investment costs for CHEST are a large uncertainty related to the potential economic market. The sensitivity analyses shows that the investment costs of the current situation are too large to be able to generate a generally feasible business case, but if the costs decrease to the possible future cost level identified, there can be a feasible case in both of the assessed markets. The Electricity-only market, however, needs a larger reduction in costs to reach the break-even point, compared to the Heat-exchange scenario.

The fuel prices are another major uncertainty to the potential market for CHEST. The fuel prices have fluctuated drastically over the last few years and the different fuel prices that have occurred just during this short period generate very different results of the economic market potential. The reference fuel price level in the reference scenario is able to induce a positive economy if this is maintained. However, if the fuel price level ends up at the levels seen before 2021, the economic market for CHEST is not economically feasible in any of the scenarios. As it is for the investment costs analysis, the Heat-exchange scenario is more economically robust than the Electricity-only scenario, but still quite sensitive.

Apart from these, another significant uncertainty is the future development of the electricity sector and the general energy supply chains in the transition of phasing out fossil fuels and introducing renewable energy. This transition can dramatically change the role for energy storage and particularly electricity storage, because large parts of the overall energy supply is to be electricfied in the coming decades. This will introduce substantial amounts of fluctuating renewables, which will likely generate larger fluctuations in the electricity prices as well, which may benefit the potential for CHEST. On the other hand, the electrification also means introduction of new demands, which are likely more flexible in time compared to traditional electricity demands. These are, for example, electric vehicle charging or the production of hydrogen using electrolysis. Flexible demands can to a large extent replace the need for storage, but the exact flexibility introduced and the “remaining” need for storage is highly unpredictable.

4.3. Competitiveness of CHEST in future market

Within the identified potential economic markets, the CHEST technology will have to compete with other storage and flexibility solutions available. Particularly Electricity-only integration of CHEST is exposed to competition, because there are many consumers and producers and many different technologies that can provide flexibility both ways. When considering this in connection with the results that indicate a low potential economic revenue in the Electricity-only market, and the result from [1] that indicate a lower energy efficiency of CHEST in Electricity-only integration compared to Lithium-ion battery storage, the possible lack of competitiveness in Electricity-only integration should be seen as a large risk.

In the heat exchange application, the starting point is better because the economic potential is better even though the market volume is lower and more niche oriented. The large difference is the ability to act on two different markets and the ability to deliver different services at different times depending on the varying energy prices. The electricity side of the system is still as exposed to competition as in the Electricity-only application, but the heat exchange systems are by nature close to a limited number of consumers and producers in a geographical area and thereby less exposed. The heat exchange market generated a better economic potential, and at the same time the results from [1] indicated that a heat exchange application of CHEST can reach a better overall energy efficiency than a Lithium-ion battery storage. In a heat exchange integration, the direct competition may not only be an electric battery though, but it could for example be a pressurized sensible thermal energy storage. This is significantly less CAPEX intensive, but will only be able to work on the heat system, and less dynamic in that way. But the competitive situation will need to be analysed in more detail for specific cases to supplement this.

4.4. Alternative technology choices of CHEST components

In this project, the CHEST system has been demonstrated in a full and combined system with latent heat storage (PCM), sensible heat storage, high temperature heat pump and organic rankine cycle. The final choice of components in the demonstrated prototype has shaped the technology assumptions through the project to supplement this. However, a CHEST system could consist of other components with other materials, etc. generating different results on other parameters, e.g. energy efficiency, economic performance or environmental impacts.

One example is the PCM in the prototype, which may be replaced with another storage medium. The total TES accounts for a large share of the total costs, about 44% of the total in the capacity ratio resulting of the capacity analysis. If a less costly PCM with similar properties could be identified, that could be a possible improvement of the economy and market potential of the technology. Alternatively, if the HP is further developed for operation at higher temperatures with a similarly good COP, known and studied cheaper PCMs could be used. An alternative could theoretically even be a sensible thermal storage instead of a latent thermal storage, though the operating characteristics and pinch points of the system would significantly be changed in this case. In case the costs for the thermal storage can be reduced relatively to the other components, this will likely alter the balance in the capacity ratio between the HP/ORC compared to the thermal storage, so that the storage will get to a larger capacity compared to the other components.

Another option could be to consider to replace the heat pump, or a share of the capacity, with a direct electric heater, to increase the electricity uptake at times with very low electricity prices and thereby save a part of the investment cost in the heat pump. This might also be used to increase the temperature further than the heat pump is able to deliver, and hence supplement the heat pump, if the storage medium and configuration allows for this. This will also reduce the capital costs, but increase the operating costs; it might in some cases be relevant to consider.

4.5. Strategic application of CHEST

In the present study, CHEST has been considered as an energy storage technology operated to reduce the energy system costs and improve the overall energy system efficiency. But energy storage can also play other roles in an energy system on the national level. From a strategic or political point of view, there can be an interest to promote energy storage to increase the national ability to integrate more renewable energy and thereby to improve the national security of supply if there are many storage systems in place.

A strategic interest like this can be implemented by regulation that allows and enables energy storage systems to enter the relevant markets, but also possibly by making a more direct economic support scheme, by investment support or a feed-in tarif for the electricity supply from the storage. For this purpose, other competing technologies to CHEST may be preferred if the economic competitiveness of CHEST is not strong. However, from a strategic point of view, it could as well be of interest to have different technologies represented in the system to diversify the technology mix and in that way reach a more robust system with a better reactivity to different situations.

Electricity storage has a key role in the transition of the European energy sector towards an emission neutral system with a high security of supply, and it enables several of the principles of the Commission energy policy. The report published by the Commission: “Study on energy storage- Contribution for the EU security of supply” [13] recognizes that balancing the grid is necessary to allow for the targeted RES penetration in the grid, but electricity storage can also enhance the security of supply, increases energy efficiency and improve market performance thus reducing final costs for consumers. In other words, energy storage can be a key enabling technology for increasing RES production in the future. In the mentioned report, the requirements for electricity storage deployment in the EU are quantified under different scenarios. To achieve the 100% RES target by 2050 the report estimates the electricity storage needs to 780 TWh. Today, the main electricity storage technology in operation in Europe is dammed and pumped hydro storage, but the possible expansion of hydro power storage is limited and cannot reach the mentioned level, which may leave a potential for other storage options. In contrary to the situation today, storage in 2050, may also be covered with indired electricity storage, such as flexible demand and sector coupling. Hence, the large potential mentioned above will not necessarily have to be covered with direct electricity storage. In any case, there will be a vary large need for flexibility services in the future to which CHEST can contribute.

4.6. Conclusions

Based on the analyses in this study on the potential economic market for CHEST from a high level national scale perspective, it can be concluded that there is an economic market for CHEST where it potentially can be economically feasible.

Two different ways of integrating CHEST in the energy system have been assessed, corresponding to the two potential markets, electricity markets and heat markets. The *Electricity-only* application only operates on the electricity market, where the *heat exchange* application operates on both electricity and heat markets.

The Electricity-only scenario shows a total market potential in the EU of 65 GW-e capacity, where the optimum capacity in terms of reduction in total costs is about 30 GW-e with a total reduction in costs of 150 M€/year. For the heat exchange scenario, the potential in the EU is smaller, about 13 GW-e for the total potential, where the economic optimum is at 6 GW-e with a total reduction in costs of 350 M€/year. With the reference cost assumptions, the Electricity-only scenario can just be paid back during its lifetime of approximately 30 year, where the heat exchange scenario generates a better economic result equivalent to a payback period of 20 years.

The results in both of the scenarios are sensitive to changes in fuel prices and how much the investment costs in the CHEST technology show a possibility to be reduced in the future. If the fuel prices return to a price level similar to the level before 2021, neither of the scenarios result in an economically feasible integration of CHEST. Likewise, if the investment costs do not decrease from the current level, the business case for CHEST is shown to be difficult.

Generally, the heat exchange scenario is more robust than the Electricity-only, even though it is also sensitive to the analysed parameters. The heat exchange scenarios may also be less affected by competition from other storage or flexibility measures than the Electricity-only scenario, due to the more specialized application and multi-energy system integration.

5. References

[1] R. Lund, M. Komoszynska, S. Stark and J. P. Herrero, "CHESRER Deliverable D6.4: Market technological potential," 2021.

[2] F. Bava, S. O. d. Eribe, A. Carrera and M. Schouten, "CHESTER Deliverable 6.1: Detailed PESTEL and PORTER analysis of the CHEST system," CHESTER, 2019, https://www.chester-project.eu/wp-content/uploads/2019/01/CHESTER_D6.1.pdf.

[3] C. N. Potter, F. Bava and M. Kowalska, "CHESTER Deliverable 6.2: Business cases definition and baseline for business models," CHESTER, 2019, https://www.chester-project.eu/wp-content/uploads/2019/10/CHESTER_D6.2_Business-cases-definition-and-baseline-for-Business-models.pdf.

[4] A. Eller and D. Gauntlett, "Energy Storage Trends and Opportunities in Emerging Markets," IFC World Bank, https://www.esmap.org/node/57868, 2017.

[5] M. Guddat, S. Sørensen, D. Trier and S. Paardekooper, "Review of the cost variation in energy plants across the 14 MSs," Heat Roadmap Europe, 2016, https://heatroadmap.eu/wp-content/uploads/2018/12/D6.2-Review-of-the-cost-variation-in-energy-plants-across-the-14-MSs..pdf.

[6] N. Duić, N. Štefanić, Z. Lulić, G. Krajačić, T. Pukšec and T. Novosel, "EU28 fuel prices for 2015, 2030 and 2050 - Deliverable 6.1: Future fuel price review," Heat Roadmap Europe, 2017, https://heatroadmap.eu/wp-content/uploads/2020/01/HRE4_D6.1-Future-fuel-price-review.pdf.

[7] H. Lund and J. Z. Thellufsen, "EnergyPLAN: Advanced Energy Systems Analysis Computer Model - Documentation Version 15," Sustainable Energy Planning Research Group, Aalborg University, Denmark. Online at www.EnergyPLAN.eu, Aalborg, 2019.

[8] P. A. Østergaard, "Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations," *Applied Energy,* pp. 921-933, 15 September 2015.

[9] Trading Economics, "EU Natural Gas - TTF Gas," 6 12 2022. [Online]. Available: https://tradingeconomics.com/commodity/eu-natural-gas. [Accessed 6 12 2022].

[10] ProPellets, "Wood pellet prices in Austria and comparisons to other fuels," ProPellets, 6 12 2022. [Online]. Available: https://www.propellets.at/en/wood-pellet-prices. [Accessed 6 12 2022].

[11] EEA, "Primary and final energy consumption in Europe," European Environment Agency, 2020. [Online]. Available: https://www.eea.europa.eu/ims/primary-and-final-energy-consumption. [Accessed 14 12 2022].

[12] EIA, "GERMANY - Primary energy," EIA U.S. Energy Information Administration, 2020. [Online]. Available: https://www.eia.gov/international/data/country/DEU/total-energy/total-energy-consumption?pd=44. [Accessed 14 12 2022].

[13] European Commission, Directorate General for Energy - Internal Energy Market, "Study on energy storage – Contribution to the security of the electricity supply in Europe," Publications office of the European Union, 2020.

[14] The Danish Energy Agency, "Teknologikatalog for energilagring (Technology catalogue for energy storage)," The Danish Energy Agency, Copenhagen, Oktober 2018 - Opdateret januar 2020.