CHESTER

Compressed Heat Energy Storage for Energy from Renewable sources

D4.9 Roadmap for future development of CHEST system

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Glossary, Abbreviations and Acronyms

ANSYS	Analysis system (software)
A-CAES	Adiabatic compressed air energy storage
AA-CAES	Advanced adiabatic compressed air energy storage
API	Application programming interface
CAES	Compressed air energy storage
CAPEX	Capital expenditure
CFD	Computational fluid dynamics
CHEST	Compressed heat energy storage
CHP	Combined heat and power
COP	Coefficient of performance
CSP	Concentrated solar power
DAM	Day-ahead market
DH	District heating
DSO	Distribution system operator
EEG	Erneuerbare Energien Gesetz (German law on renewable energies)
EES	Electrical energy storage
EES	Engineering equation solver (software)
ENTSO-E	European network of transmission system operators for electricity
ETD	Energy Taxation Directive
FES	Flywheel energy storage
FRR	Frequency restoration reserve
GIS	Geographical information system
GWP	Global warming potential
HP	Heat pump
HT	High-temperature
HTC	Heat transfer coefficient
HTF	Heat transfer fluid
HTHP	High-temperature heat pump
HT-TESS	High-temperature thermal energy storage system
HTWT	High-temperature water tank
HX	Heat exchanger
IE	Isobaric expansion
IEA	International Energy Agency
IMST-ART	Simulation tool to assist the selection, design and optimization of refrigerant equipment and components
IRR	Internal rate of return
KER	Key exploitable result
KPI	Key performance indicator
LAES	Liquid air energy storage
LCA	Life cycle analysis
LCOS	Levelized costs of storage
LH-TES	Latent heat thermal energy storage (latent part of the HT-TESS)
LT	Low-temperature
LTTES	Low-temperature thermal energy storage (seasonal thermal energy storage)

LTWT	Low-temperature water tank
MATLAB	MATLAB software
mFRR	Manual frequency restoration reserve
NBP	Normal boiling point
ODP	Ozone depletion potential
OPEX	Operational expenditure
ORC	Organic Rankine cycle
PCM	Phase change material
PHS	Pumped hydro storage
PLC	Programmable logic controller
PtG	Power-to-gas
PtL	Power-to-liquid
PtX	Power-to-X
P2P	Power-to-power
PV	Photovoltaics
R&D	Research and development
RES	Renewable energy source
RPM	Revolutions per minute
RR	Restoration reserve
SH-TESS	Sensible heat thermal energy storage system (sensible part of the HT-TESS)
SMES	Superconducting magnetic energy storage
SoC	State of charge
T&D	Transmission and distribution (electricity grid)
TES	Thermal energy storage
TRL	Technology readiness level
TRNSYS	Transient system simulation (software)
TSO	Transmission system operator
VVT	Variable valve timing

1. Introduction

1.1. Executive summary

In the CHESTER research project, lasting from 04/2018 until 03/2023, the 12 European partners involved lifted the so-called CHEST (Compressed Heat Energy Storage) technology of an innovative power-to-heat-to-power energy storage system from a technology readiness level (TRL) of 3 up to a TRL of 5. The CHEST system is composed of three main components: a high-temperature heat pump (HTHP) for the uptake of (renewable) electricity and low-temperature heat, a high-temperature thermal energy storage system (HT-TESS) for the storage of the high-temperature heat delivered by the HTHP and an Organic Rankine Cycle (ORC) machine, driven by this high-temperature heat, for the generation of electricity and low-temperature heat. The HT-TESS consists of a latent heat thermal energy storage (LH-TES) with a phase change material (PCM) as the storage medium, and a sensible heat thermal energy storage system (SH-TESS) with pressurized hot water as the storage medium. Furthermore, the CHEST system can be combined with a low-temperature thermal energy storage (LTTES), i.e. a seasonal thermal energy storage that on the charging side facilitates the uptake of heat from renewable sources and serves as a heat source for the HTHP and on the discharging side supplies heat to a district heating (DH) system and serves as a heat sink for the ORC, see Figure 1.

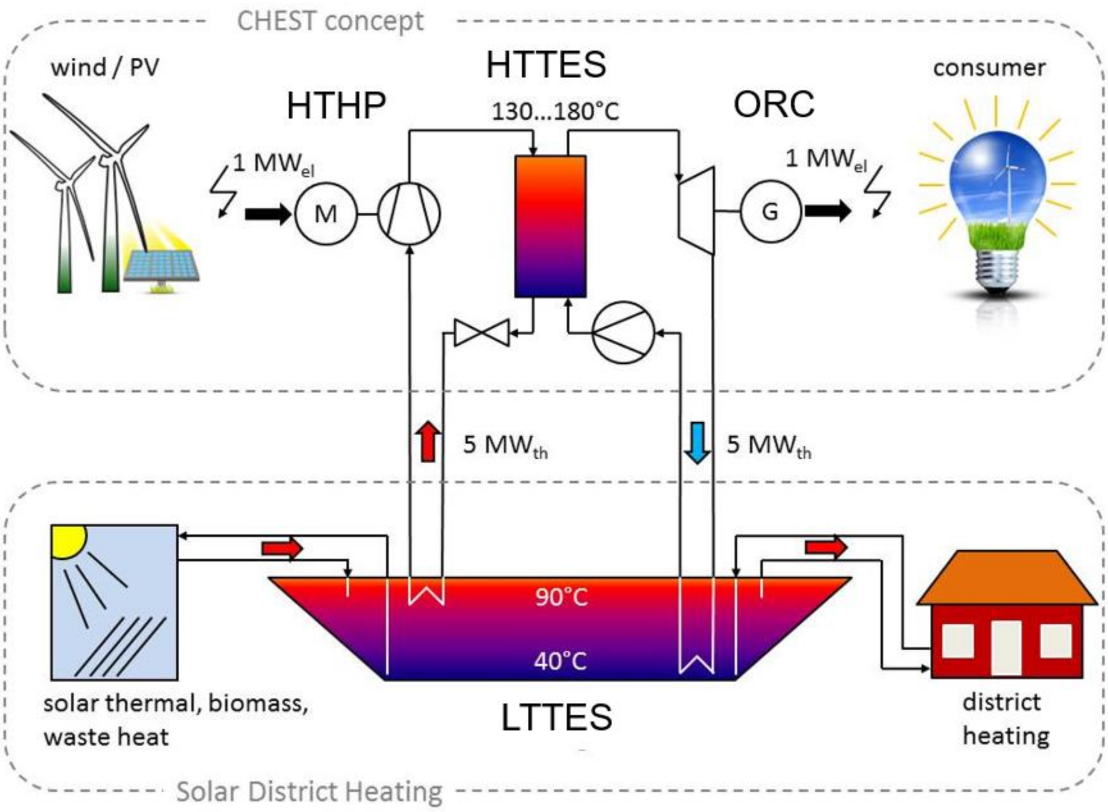

Figure 1: Schematic drawing of the CHEST concept (Source: DLR).

Figure 1 shows indicative numbers for the temperatures in the HT-TESS and LTTES as well as the electric and thermal input and output of the system. A major advantage of the system is its flexibility concerning heat and electricity output dependent on the respective boundary conditions. This means that mainly by varying the HTHP heat source and ORC heat sink temperature, the output can be shifted towards either thermal or electric resulting in different power-to-power (P2P) ratios of the system.

In principle, the CHEST system is based on existing technology (HP, TES, ORC), but ground-breaking advancements had to be made in the CHESTER research project to adapt the main components to CHEST´s specific needs and allow for an efficient and cost-competitive overall system.

A key achievement of the project was the development, construction and experimental testing of a first-of-its-kind CHEST prototype with an electric power of the HTHP and the ORC in the order of magnitude of about 10 kW_{el}. Several charging and discharging tests were performed in order to demonstrate the proof-of-concept, analyze operating modes and system parameters and gain operational experience with the system. Furthermore, an isobaric expansion (IE) engine pump was developed and experimentally tested. Such IE engine pumps can replace the high-pressure pump of the ORC and thus increase the net electricity generation of the ORC, but they can also be used for other applications beyond CHEST, e.g. for the use of waste heat from hydrogen fuel cells or diesel engines to generate electrical power.

Beside this constructional and experimental work on the CHEST individual components and the first-of-its-kind prototype of the overall system, the project partners carried out comprehensive theoretical analyses on the applications and integration of the CHEST system in the current and future energy system. With the help of dynamic simulation models developed in the CHESTER project, simulations for the use of CHEST in different case studies were performed in order to evaluate the CHEST system from a techno-economic perspective. The use of CHEST and its relevance in the future energy system was also analyzed at the scale of national energy systems. Furthermore, a life cycle analysis (LCA) was carried out showing the environmental impact of the CHEST system and its individual components and materials, respectively. Further achievements in the CHESTER project were the development and analysis of business models, the development and validation of a Smart Energy Management System (SEMS) as a set of tools defining an optimized control strategy for the operation of CHEST, and the development of a web tool giving the potential user a quick view on the proper dimensions and the economic viability of CHEST in two selected use cases.

Based on this theoretical and experimental outcome, the project partners discussed the future perspectives of CHEST and identified the most promising applications and business models. Given the current status of the CHEST technology at a TRL of 5, further development is required towards operation of CHEST at commercial scale. The project partners identified the challenges the CHEST technology currently still faces and formulated the necessary steps for the future development of the CHEST system, both from technological as well as non-technological perspective.

This report is a roadmap for the future development of CHEST. It gives an overview of the main project results and highlights the key innovation gaps and challenges of the technology at its current status. Based on this, the report presents the required R&D work for the next decade(s) to get the CHEST technology into commercial applications of relevance to the energy system described in this report at hand.

From a technological point of view, the three main components HTHP, HT-TESS and ORC that form a CHEST system, were successfully developed and adapted to the particular requirements of a CHEST concept. After stand-alone testing, they were integrated to a first-of-its-kind prototype of the CHEST system. The experimental tests of this CHEST prototype clearly demonstrated a proof of the CHEST concept and provided valuable operational experience with the CHEST system.

A major requirement in the further technological development of CHEST is the scale-up of the system from the current size of the first-of-its-kind prototype of about 10 kW_{el} of charging and discharging power up to charging and discharging powers in the MW_{el} scale. In order to achieve this, demonstration projects are required as a next step with CHEST systems operating in an intended environment. This will further increase the TRL of the CHEST technology as well as advance manufacturing aspects, increase efficiencies and reduce costs.

Several essential measures to increase the efficiency and reduce the investment costs of a CHEST system were identified. The efficiency increase can mainly be achieved by the use of turbomachinery for the HTHP and the ORC, which will be a result of the scale-up. An important measure for the reduction of the investment costs is the partial or complete combination of HTHP and ORC in one and the same component. Furthermore, a huge potential for efficiency increase and cost reduction is given by respective changes in the concept and design of the LH-TES, e.g. by using an alternative phase change material (PCM), applying an active storage concept and using a single-tube heat exchanger instead of a dual-tube one.

From a non-technological point of view, the analyses in the CHESTER project showed that it is currently difficult to achieve economic viability for a CHEST system offering different electricity and/or heat services. For instance, the revenues CHEST can make from the participation in different electricity markets are generally low compared to the CAPEX of CHEST, which is due to relatively low electricity prices and price fluctuations in these markets and high CAPEX of the technology based on current designs and technology maturity level. When CHEST provides both electricity and heat services, e.g. for an energy community or an industrial park, this can be economically beneficial. However, it is important to mention that there is an inverse relationship between these electricity and heat services, i.e. that increasing the one output will be at the expense of the other output. This means that for instance the achievement of a high P2P ratio (ratio of electrical output to electrical input) might even result in a net heat demand of the CHEST system meaning that more heat is required at the HTHP evaporator than generated at the ORC condenser.

When it comes to providing the service of electricity storage, the CHEST technology faces several competitors, the most important ones being pumped hydro storage (PHS), compressed air energy storage (CAES) and partly also batteries, because these storage technologies are similar in terms of storage capacity and power. However, compared to PHS and CAES, CHEST has the huge advantage of having no geographical constraints, which clearly limits the further increase of PHS and CAES capacities. From a strategic point of view, this may be one of the most important arguments for the further development of CHEST technology, since the further increase of the renewable electricity generation will definitely require a massive increase of electrical energy storage capacities and this cannot be covered by PHS, CAES and batteries.

Nevertheless, given the number of existent competitors in the field of electrical energy storage and the fact that for instance batteries have typically higher electrical roundtrip efficiencies than CHEST, it will be difficult for CHEST to be economically viable as an electricity-only storage.

Therefore, heat integration, i.e. the uptake of waste heat or other renewable heat sources and the supply of heat to e.g. industrial consumers or a district heating system, is expected to be a vital part of CHEST application. This means that CHEST is indeed supposed to contribute significantly to the stability of the electricity grid by taking up surplus electricity from fluctuating renewable electricity sources, but it needs to be installed at such locations that allow a reasonable heat integration of CHEST and an economic benefit for CHEST also on the heat side. Then, it is exactly this coupling of the heat and electricity sector in a smart and flexible way that makes CHEST a unique and advantageous storage solution.

1.2. Purpose, scope and methodology

This report presents the outcome of the elaboration of a roadmap for the future development of CHEST technology towards commercial application. This comprised the following main subtasks:

- collection of main project results and conclusions, giving an overview of the current status of the CHEST technology at the end of the CHESTER research project,
- based on that, the identification of required both technological and non-technological progress to overcome the existing challenges,
- identification of required R&D work for the CHEST technology,
- identification of other technologies competing with CHEST, their stage, potential and future development,
- formulation of key messages concerning the current development stage as well as the future relevance of the CHEST technology,
- definition of CHEST´s future perspectives, i.e. CHEST´s significance for the energy system as well as the most promising applications and business models,
- support of exploitation activities of the CHESTER project.

The different theoretical and experimental results achieved throughout the project served as a basis for the formulation of the current status of the CHEST technology and the identification of the required progress for the further development. Beside the collection and analysis of the project results, the work here was mainly based on discussions among the partners dedicated to specific topics such as investment and operational costs of the main components, technological challenges in the construction and operation of the main components and the prototype of the CHEST system or the configuration of the CHEST system adapted to different use cases. The identification of future applications and business models was mainly also the result of dedicated discussion meetings among the partners and also included some literature research in terms of for instance the characterization of technologies competing with CHEST. Furthermore, the roadmap and the exploitation activities complemented one another in the formulation of CHEST´s future perspectives.

1.3. Structure of this document

In Chapter 2 of this report, the main project results are summarized in order to give a brief overview of the development of the CHEST technology that was achieved in the CHESTER research project. By showing the current status of development, this overview of project results also sets the basis for the identification of the required progress of CHEST technology towards commercial scale application – both from a technological (Chapter 3) and a non-technological (Chapter 4) point of view. Since the focus of this report is on the key messages and future perspectives of CHEST, the project results are presented only briefly. More detailed results can be found in the respective public reports of the project [Del 2023] that are available on the website of the project, see link below.

In Chapter 5, the required R&D work identified from the analysis of the required technological and non-technological progress is presented.

Chapter 6 deals with the main competitors of CHEST. These technologies are discussed concerning their current stage of development as well as their future development. Furthermore, advantages and disadvantages are listed to show the competitiveness of CHEST for different applications.

Chapter 7 presents the key messages of the CHESTER project. These are the main conclusions that were drawn in several discussions by the partners.

This is the basis for the formulation of CHEST´s future perspectives, i.e. the determination of the relevance of CHEST in the future European energy system, the preferred applications and respective business models in Chapter 8.

Finally, Chapter 9 presents an overall conclusion.

1.4. Relations with other reports

The report at hand uses results and information from nearly every previous work in the CHESTER project. In fact, all these results together with the experiences of the different partners gained throughout the project were the basis for the dedicated discussions and the elaboration of the key messages on the CHEST technology presented here. In particular, there was a strong relationship between the future development roadmap and the exploitation activities. On the one hand, the conclusions formulated in the report at hand served as input for identifying appropriate funding schemes for enabling further development of the CHEST technology. On the other hand, discussions held within the roadmap and exploitation activities often targeted objectives from both activities such as the formulation of CHEST´s future perspective and the analysis of key exploitable results (KER).

All public reports of the CHESTER project [Del 2023] are available on the website of the project: https://www.chester-project.eu/public-documents/.

2. Main project results and conclusions

2.1. Main technological results

The following subchapters briefly deal with the most important project results of the main components that form the CHEST system as well as the project results that were obtained for the complete CHEST system. This will comprise all significant results and observations, advantages and drawbacks observed during the technological development, the construction phase as well as the experimental testing of the components and the complete CHEST system, respectively. For more detailed results, please refer to the public reports of the CHESTER project [Del 2023] on the website: https://www.chester-project.eu/public-documents/.

2.1.1. High-temperature heat pump (HTHP)

In the CHESTER project, a high-temperature heat pump (HTHP) was designed, built and tested. It uses low-temperature heat between about 70 - 100 °C and preferably renewable electricity to deliver high-temperature heat of up to about 150 °C. It uses R1233zd(E) as the refrigerant, which is non-flammable, non-toxic and has both a low GWP and a very low ODP. The boiling point at atmospheric pressure (NBP) of ca. 18 °C is sufficiently low to allow for a wide range of low-temperature heat sources. The critical temperature of R1233zd(E) accounts for about 166 °C, which is high enough for the abovementioned condensing temperature of about 150° C.

For the HTHP prototype built in the CHESTER, project, a suitable compressor was selected and tested prior to the construction of the whole HTHP. It is a single piston reciprocating compressor with a wide range of motors speeds. Lubrication is also an important issue that was tackled during the development of the HTHP, especially due to the fact that there was a lack of data on suitable lubricants for the selected compressor. Two oils were tested with the refrigerant R1233zd(E) at various concentrations and for a range of temperatures and pressures in order to understand oil-refrigerant interaction and select a suitable oil for the HTHP of the CHEST prototype.

After the testing of the compressor, the whole HTHP prototype was designed, including the heat exchangers (evaporator, condenser, subcooler), the electronic expansion valve, and several other auxiliary components such as valves, flow switches and the refrigerant lines. Furthermore, the HTHP prototype was equipped with a stand-alone control system based on a PLC unit including a complete in-house control algorithm.

The experimental testing of the HTHP prototype with a heating capacity of around 35 kW_{th} for the condenser and 25 kW_{th} for the subcooler under nominal operating conditions showed satisfactory performance with COP values between 3 and 7 depending on heat source and sink temperatures and motor speeds. In general, the prototype operated well under the required boundary conditions and the control algorithm developed for the prototype operated satisfactorily. A maximum condensing temperature of 148 °C could be achieved. Vibrations were found to be an issue at some compressor motor speeds.

After these stand-alone tests, the HTHP was integrated into the prototype of the complete CHEST-system, see Section 2.1.5. While the stand-alone tests focused on a steady-state performance evaluation in the full operating range, the integrated tests focused on the system operation and dynamic performance of the HTHP when connected to the HT-TESS system.

2.1.2. Organic Rankine cycle (ORC)

An Organic Rankine Cycle prototype with a power output of about 10 kW_{el} for the integration into a CHEST system was designed, built and tested in the CHESTER project. It uses the refrigerant R1336mzz(E) (also known as DR-12), which has zero ODP and a low GWP. Special attention was paid to the ORC operation under off-design conditions, i.e. the adaption of the expander to strong transient loads resulting from varying sink temperatures and varying electricity demand from the electricity grid. Thus, the challenge was to select and operate an expander with satisfactory performance also under part-load conditions. A piston expander with variable valve timing (VVT) was selected for this reason. This means a variation of the internal expansion ratio in order to match the transient loads imposed on the ORC, and it is realized by the integration of a control algorithm that controls the timing of the expander inlet valve.

The general control of the ORC is based on a constant degree of superheating of 5 K at the inlet of the expander. Superheating at the inlet of the expander is required to ensure safe expander operation away from the two-phase-region. This is primarily achieved by adapting the refrigerant mass flow rate by changing the pump speed, but can also be done by changing the expander speed or by changing the heat source temperature or mass flow rate (heat source changes can only be done in separate ORC operation, not when integrated into the CHEST system).

After the construction of the ORC test rig, experiments were carried out for a wide range of operating conditions. Different input parameters were analyzed in the experimental campaign, for instance: RPM of the expander, RPM of the pump, mass flow and temperature of the coolant (heat sink), mass flow and temperature of the oil (heat source), and opening degree of the valve. A maximum power output of around 8.1 kW_{el} was achieved with the prototype under the boundary conditions used within the tests. Cycle efficiencies were found to be in the range 3.1 - 6.7%. A further important outcome of the experiments was the analysis of the variable valve timing mechanism by studying the influence of expander valve position and parameters such as pressure ratio and expander speed on the expander efficiency.

After these stand-alone tests, the ORC was integrated into the prototype of the complete CHEST-system, see Section 2.1.5. While the stand-alone tests focused on a steady-state performance evaluation in the full operating range, the integrated tests focused on the system operation and dynamic performance of the ORC when connected to the HT-TESS system.

2.1.3. High-temperature thermal energy storage system (HT-TESS)

Given the nominal point operation of the charging and discharging cycles as boundary condition, a high-temperature thermal energy storage system (HT-TESS) system was designed, which consists of a latent heat thermal energy storage (LH-TES) and a sensible heat thermal energy storage system (SH-TESS).

The LH-TES uses a eutectic mixture of potassium and lithium nitrate as a phase change material (PCM) with a melting temperature of 133 °C according to the literature [Tamm 2008] [Roge 2013]. Due to the low thermal conductivity of the PCM, heat transfer from and to the PCM is a key challenge to consider in the design of the LH-TES. With the help of comprehensive transient simulations (see Section 2.2.3), the design of a special finned-tube heat exchanger immersed in the PCM containing storage tank was developed and optimized. Optimization comprised the determination of parameters such as number, length and diameter of the heat exchanger (HX) tubes and the detailed fin design. Since the charging and discharging cycles operate with different refrigerants, the heat exchanger is of dual-tube concept to separate the two refrigerant circuits. While steel is chosen as material for the tubes, the fins are made of an extruded aluminum alloy.

The SH-TESS consists of a hot and a cold water tank that are connected to the subcooler of HTHP and the preheater of the ORC to form one closed circuit. Pressurized water is used as the heat transfer fluid (HTF). It is pumped from the cold tank to the hot tank with heat uptake in the HTHP´s subcooler during charging and it is pumped from the hot tank to the cold tank with heat rejection via the ORC´s preheater during discharging. To compensate for volume changes and to prevent the storage medium from evaporating, the two SH-TESS tanks are equipped with a nitrogen pressure control system.

2.1.4. Isobaric expansion engine-pump

Based on earlier studies and on thermodynamic modeling (see Section 2.2.4), an isobaric expansion (IE) engine pump was developed and built. An experimental setup was designed and built to analyze energy conversion efficiency and power density of the IE engine pump under various operating conditions (heat source temperature, head pressure). The experimental campaign showed a very high efficiency of 4 - 6% for heat source temperatures of 30 - 90 °C and a power output of the IE engine pump of 100 - 1,000 W, depending on operating conditions.

This developed and experimentally tested IE engine pump was a Worthington-type engine which was found to be more suitable for application as a high-pressure pump in the ORC of a CHEST system compared to the Bush-type engine. However, in order to be able to develop an extension of performance maps from laboratory scale to real size engines, experiments were also conducted with a Bush-type IE engine pump with a power output of 5 - 20 W. The thermal efficiency of this Bush-type IE engine pump was found to be at least 5% for heat source temperatures of 60 - 95 °C, which can mainly be explained by the involvement of heat regeneration.

As a general conclusion, the experimental results are very promising and in line with the theoretical predictions, for both Bush- and Worthington-type engine pumps. There are no other heat engines operating at such low temperature differences with so high efficiency and power density. The experiments initially revealed several issues with corrosion and also with piston sealing, which led to operating and sealing improvements to overcome these issues.

The developed IE engine pumps can be used for different applications in a CHEST system and beyond. In the CHEST system, they can replace the high-pressure pump of the ORC as a main electricity consumer thus increasing net electricity generation of the ORC. The IE engine pump can also pump any other liquid of the CHEST system by driving the respective pumps directly using available low-grade heat without use of electricity.

Furthermore, in view of the results obtained, the IE engine pump can be driven by heat rejected in the ORC cycle, thus without using an external energy source.

2.1.5. CHEST system

A first-of-its-kind CHEST prototype consisting of the HTHP (see Section 2.1.1), the ORC (see Section 2.1.2) and the HT-TESS (see Section 2.1.3) was built and tested in the laboratory environment under a wide range of testing conditions. The IE engine pump described in Section 2.1.4 was not a part of this prototype, since its development had been decoupled from the build of the prototype for practical reasons.

After the preparation of the laboratory, and the installation and commissioning of the prototype (including safety approval), eleven experimental tests were carried out, either as full-cycle tests (charging and discharging) or as partial tests analyzing only the charging/condensation performance of HTHP and HT-TESS or the discharging/evaporation performance of HT-TESS and ORC, respectively. This testing and analysis hereof are detailed in the respective report on the results of the experimental testing of the prototype [Del 23-d]. The test conditions were varied, for instance, concerning HTHP heat source temperature, compressor speed and mass flow rate, ORC expander speed, mass flow rate and valve position and the pre-conditioning of the LH-TES and the SH-TESS.

The commissioning as well as the experimental tests gave comprehensive insight into the performance of the prototype CHEST system and provided valuable experiences for the build and operation/handling of such a system. Main findings in the handling of the system were for instance: a suitable procedure for filling the PCM into the LH-TES by stepwise mixing, pouring and heating, the appearance and spread of vibrations from the HTHP and ORC to the other components and the influence of the type of connections on this issue as well as resonant frequencies due to these vibrations, and the distribution of refrigerant in the various pipes and reservoirs of the system incl. dealing with refrigerant leakage.

The testing of the CHESTER laboratory prototype gave a proof-of-concept for the theoretical and simulation work done within and prior to the CHESTER project and allowed to gain operational experience of such an innovative system. With the insight gained and lessons learned, further developmental work and upscaling are possible. The experimental testing gave insight into power modulation and combined characteristics when, for example, the ORC mass flow rate and expander speed are ramped. Overall, both the HTHP and ORC showed good dynamic behavior and power modulation. For the ORC, the current startup procedure requires significant heat to preheat the system. Further tuning and automation of the startup procedure allows for faster steady-state operation and decreased losses during the startup phase. The initial testing of the system controls thus showed the need for further development in larger scale follow-up prototypes.

In charging operation of the reference test, as an example, the operation stage of combined operation of the HTHP and HT-TESS was 4.7 h with an average consumed power of 10 kW_{el} and an electrical energy of 45.5 kWh_{el}. During discharging in this test, the combined HT-TESS and ORC operation provided 10.9 kWh_{el} at a power between 5 and 8 kW_{el}. The system operation stage was 1.6 h in duration. From all the tests, the maximum electricity generation was 9 kW_{el}.

The efficiencies of the HTHP and the ORC were different compared to the stand-alone tests of these components, cf. Section 2.1.1 and 2.1.2. In the stand-alone tests, a wide range of heat source and sink temperatures was applied in order to analyze the behavior also under extreme conditions that are not present when the HTHP and ORC are integrated in a CHEST system. Furthermore, some improvements for instance concerning the ORC expander cooling were already implemented as a conclusion of the stand-alone tests. While the HTHP showed COPs between 3 and 7 in the stand-alone tests, the COP was between 3.7 and 5.6 in the tests of the complete CHEST system. For the ORC, the efficiencies were in the range of 3.1% to 6.7% in the stand-alone tests and between 5.0 and 6.7% in the tests of the complete CHEST system.

The roundtrip efficiency, defined by the product of the efficiencies of the main components HTHP, HT-TESS and ORC, was in the range 17.9% to 37.2%. The net power ratio, which is the ratio of net supplied electrical energy of the ORC to the electrical energy consumed by the HTHP in a full-cycle test including transient phases of the HTHP and ORC, accounted for 20 - 21%. The overall roundtrip utilization rate, i.e. the ratio of the energy sum needed to discharge the system to the energy sum provided by charging the system, varied between 51 and 62%. Note that these figures can only give a rough estimate, which is due to the testing conditions.

2.2. Main results on modeling and simulation

The following subchapters briefly describe the models that were developed within the CHESTER project and the simulation work carried out with these models. Main scope and functionalities, but also limitations are discussed. For more detailed information, especially regarding the simulation results, please refer to the public reports of the CHESTER project [Del 2023] on the website: https://www.chester-project.eu/public-documents/.

2.2.1. Modeling of the HTHP

Once the refrigerant and the compressor had been selected, a detailed physical-based model in the software IMST-ART was developed to help select the heat exchangers of the heat pump. The model was used for the selection and pre-sizing of the components in the heat pump cycle as well as for assessing the performance of the HTHP for different boundary conditions. Experimental results were then used to adjust and validate the IMST-ART simulation model, i.e. the model parameters were finally fitted once the experimental campaign was available and the IMST-ART model also helped to obtain extended performance maps. One of the issues that were found with the IMST-ART model when comparing with the experimental results is that the real compressor efficiency was finally of around 51 - 55% instead of the initial estimation of 60%. The real thermal losses of the compressor were also higher than the initial estimation (45% instead of 19%).

2.2.2. Modeling of the ORC

The thermodynamic modeling of the Organic Rankine Cycle was done by a steady-state model developed in Python. The model served for calculations of temperatures, mass flow rates, the power output of the expander, the efficiency of the power cycle and the pressure drops in the heat exchangers. Furthermore, an exergy analysis is included in the model, which quantifies the exergy losses in the expander, the heat exchangers as well as in the complete power cycle. The fluid properties are called from the REFPROP database. With this steady-state Python model, thermodynamic calculations were carried out for different working fluids.

The model was fine-tuned based on the experimental results. Electrical power output of the ORC could then be calculated with a deviation of about 3.1% between simulation and experiment.

Furthermore, a Python simulation model for the generation of performance maps was developed. This model only contains four basic components: the pump, the evaporator, the expander and the condenser. It uses simplified approaches such as a constant isentropic efficiency of the pump and constant pinch-point modeling of counter-flow heat exchangers for the evaporator and condenser. The isentropic efficiency of the expander is expressed in dependence of the input parameters and this expression is derived from the experimental results of the ORC prototype.

2.2.3. Modeling of the HT-TESS

Heat transfer from the working fluid to the PCM during charging and from the PCM to the working fluid during discharging is the crucial process to consider in the design of the HT-TESS and its internal finned heat exchanger tubes. Due to the branched geometry of this internal heat exchanger as well as the phase change processes in both the PCM and the working fluid, it is a very complex process including temporal and spatial variation of the heat transfer, which requires transient simulations.

A MATLAB®-based model for the transient simulation of thermal energy storage with PCMs developed by DLR was adapted and expanded in the CHESTER project to the requirements of the LH-TES prototype. This model couples two submodels:

- a **storage model** for the PCM and the heat exchanger with discretized finite volume mesh
- a quasi-steady two-phase **flow model** for the working fluid with discretized one-dimensional finite difference mesh

The coupling of these two submodels and implicit temporal discretization allows for the calculation of the temperature inside the LH-TES and the liquid phase fraction of the PCM. The model helps determining the basic design parameters of the heat exchanger such as number, length and diameter of the HX tubes for a given heat transfer coefficient by calculating the temperature inside the LH-TES as well as the heat transfer rate over time.

The detailed design of the finned heat exchanger tubes was then analyzed from thermodynamic point of view by simulations carried out in ANSYS® Fluent. For different variants of the finned dual-tube HX, the radial heat conduction and temperature distribution as well as the melting characteristics (evolution of liquid fraction in the PCM) during charging and discharging can be studied. The transient model is two-dimensional and represents the HX design embedded in a hexagonal PCM volume. In combination with requirements from structural and manufacturing point of view, the final design of the finned dual-tube HX can be determined by this model.

Furthermore, a MATLAB® tool was developed for the design of the SH-TESS storage system. It calculates the basic thermodynamic states for charging and discharging and is based on nominal point operation, since the operation parameters are almost constant during charging and discharging. Thus, no transient simulation is required for this component. The most important outcome of this MATLAB® tool for the SH-TESS is the required volume of the hot and cold tank.

2.2.4. Modeling of the IE engine-pump

In the CHESTER project, an existing thermodynamic model of a Bush-type isobaric expansion (IE) engine was extended to take into account the effects of internal (dead) volumes and frictional pressure drop in the required heat exchangers (heater, cooler, regenerator). For given heat source and sink temperatures, the model allows detailed study of these two effects on the thermal efficiency of the engine.

Heat regeneration is crucial for achieving high thermal efficiencies. However, it causes additional pressure drop and dead volumes (as explained above). Consequently, designing heat exchangers and regenerators/recuperators for Bush type IE engines is a difficult task, as the positive effects of regeneration/recuperation may be reduced by the dead volume effect of required heat exchanger equipment and frictional pressure drop. The model helps in developing optimal heat exchanger design for the IE engine. Beside the analysis of different heat exchanger designs, the model was also used for studying different working fluids and mixtures of working fluids including supercritical operation. For this purpose, the model was implemented in MATLAB and coupled with REFPROP for delivering the relevant fluid properties. Studies performed affirmed the importance of the application of very compact heat exchangers for Bush type IE engines.

Furthermore, the theoretical background for determining the efficiency of regeneration has been developed. It permits the obtainment of thermodynamic limits on the heat regeneration in the case of arbitrary working fluids. The results of this development were used for evaluation of the heat regeneration efficiency and calculation of the IE engine-pump thermal efficiency. The experimental results were found to be in line with the theoretical predictions, for both Bush- and Worthington-type engine pumps.

2.2.5. CHEST system models

Throughout the CHESTER project, several simulation models of different complexity, level of detail and specific purpose were developed. They were used for analyzing the performance of the CHEST system and its main components mainly from energetic and economic point of view. In the following, the most important characteristics of the models are explained briefly:

<u>Steady-state EES model</u>

A steady-state EES model was developed that includes all main components of the CHEST system (HTHP, ORC, LH-TES and SH-TESS) and their most important parts, such as heat exchangers, compressor and expander, pumps and expansion valve, the high-temperature water tank (HTWT) and the low-temperature water tank (LTWT). It is a simple model with no consideration of heat losses and neglecting pressure drop in the heat exchangers, with constant latent to sensible heat flux ratios and saturated refrigerant conditions, but through the thermo-physical properties database incorporated in EES, it allows for CHEST performance calculations for various refrigerants.

This steady-state thermodynamic model in EES was a preliminary model used in an initial stage of the project to only compare the refrigerants and to estimate the capacity of each component. It was used to compare the potential performance of different cycles and refrigerants, leading to the conclusion that R1233zd(E) was a good candidate for the heat pump, and that a single stage was sufficient to reach the desired performance.

First simple TRNSYS model

A TRNSYS model that used performance maps for the HTHP and the ORC that had previously been calculated in the software Ebsilon was developed. The performance maps had been calculated for two refrigerants, butene and R1233zd(E), for a range of heat source and sink temperatures. The PCM used in the TRNSYS model was the eutectic mixture of potassium and lithium nitrate KNO_3-$LiNO_3$ with a melting temperature of 133 °C. The HT-TESS is simulated in a relatively simple way, i.e. by integrators considering only the current state of charge (SoC) of both the latent (LH-TES) and sensible (SH-TESS) part of the HT-TESS, but without taking storage temperatures into account and also neglecting thermal losses. However, possible nonuniform charging and discharging of the LH-TES and SH-TESS is compensated by a special “clean-up strategy” that dissipates excess heat in one of the storage parts and transfers it to the heat source. A key characteristic of this first TRNSYS model is the integration of an LTTES (i.e. seasonal or pit thermal energy storage) that serves as a heat source for the HTHP and as a heat sink for the ORC. In a later modification of the model, condensation heat of the ORC could also be transferred to the environment.

This TRNSYS model was used to simulate the performance of a CHEST system in altogether 5 case studies (Aalborg, Alpha Ventus, Turin, Ispaster, Barcelona) and compare the results to the case without CHEST system (i.e. only the use of an LTTES). The purpose and outcome of the model was purely energetic, not economic. Main output variables were the amounts of electricity absorbed by the HTHP and generated by the ORC, full-load hours of the HTHP and ORC, COP, ORC efficiency and roundtrip efficiency (P2P ratio).

TRNSYS model for analysis of operation modes

In parallel and as an upgrade to the first simple TRNSYS model described above, another relatively simple TRNSYS model was developed that focuses on the analysis of the several operation modes of CHEST concerning a different ratio of electricity and heat output and thus an adaption of the roundtrip efficiency. Furthermore, this model has a stronger focus on the individual components in order to define their requirements and to allow for an analysis at both the system and the component level.

The TRNSYS model uses performance maps calculated from the steady-state EES-CHEST model (see above) for butene as HTHP and ORC refrigerant and KNO_3-$LiNO_3$ with a melting temperature of 133 °C as the PCM. Both the LH-TES and the SH-TESS are simulated by simple adiabatic models, but in contrast to the first simple TRNSYS model, there is already a separation between the HTWT and LTWT in this model. An LTTES is not implemented, but the operation modes are defined by different (constant) heat source and sink temperatures.

As an input to the model, design month profiles for RES electricity and heat production and demand indicating summer, winter or transitional periods are used. The main output parameters for the analysis of the altogether six different operation modes are the roundtrip efficiency, the charging and discharging time and the corresponding amounts of electricity absorbed by the HTHP and generated by the ORC, as well as excess RES electricity that cannot be used due to CHEST size limitations.

Advanced TRNSYS model

At a later stage of the project, an advanced TRNSYS model with a much more detailed simulation of the CHEST system and its components was developed. One main difference compared to the earlier TRNSYS model is that the HTHP and ORC cycle performance and their respective electrical and thermal power are not represented by implemented performance maps that had been created before. Instead, the HTHP and the ORC are integrated with their main components (compressor, turbine, heat exchangers, pump, etc.) and the calculation of the refrigerant state (temperature, pressure, enthalpy) at every important point of the cycle directly in the TRNSYS model. Special TRNSYS types were developed for components such as the compressor, turbine, preheater, condenser and some others. Furthermore, the LH-TES and the SH-TESS are implemented in a much more detailed way, including heat transfer limitations between refrigerant and PCM, storage temperatures, thermal losses, minimum volume in the HTWT and LTWT and pumping between these two tanks. An LTTES is not part of the model; instead, heat source and sink are given by constant waste heat and district heating network temperatures, respectively.

The model was originally developed for the simulation of a CHEST system participating in both the spot and the tertiary balancing market, but it was later adapted for also simulating a CHEST system acting in a local energy system with PV electricity and solar thermal and biomass heat generation up to the case where this forms an island energy system with no electrical grid connection. Accordingly, different types of system control based on either electricity prices or electricity generation and demand were implemented.

The advanced TRNSYS model delivers a comprehensive list of energetic, operational and economic output parameters of the CHEST system and its main components. Since the model is suitable for different refrigerants as well as PCMs, an analysis of a range of refrigerant/PCM combinations was carried out to find out the most promising ones regarding CHEST performance and economic profit. Later on, the two case studies for Aalborg (CHEST system participating in the electricity markets) and Ispaster (CHEST system acting in a local energy system) were studied more in detail with the advanced TRNSYS model in order to evaluate the performance of the CHEST system by means of defined key performance indicators (KPIs).

A further development of the advanced TRNSYS model was carried out with the implementation of a smart energy management system (SEMS) allowing for a CHEST operation that is better adapted to the external boundary conditions (electricity prices, electricity generation and demand) including their forecast. The SEMS is not a model as such, but in principle an optimizer that consists of different tools including the TRNSYS model as well as modules for the forecast of e.g. electricity prices and meteorological data.

EnergyPRO model for analysis of economic performance

A simplified CHEST system was modelled in the energyPRO software. EnergyPRO is designed for local energy system simulation and optimization, and considers mainly energy conversion, storage and demands at the hourly aggregation level and includes all energy flows between the model components and interaction with external energy markets, but does not consider mass flows, hydraulics and other technical details. In the models of the CHESTER project, the flows between the main CHEST components (heat pumps, thermal storage and ORC) and its environment (electricity grid, heat source and sink) have been included. Based on electricity prices, taxes and fees, the model tries to find an optimum CHEST operation in terms of economic revenue.

Several energyPRO models were developed for the simulation of different case studies: for the grid-based purchase and sale of electricity without any constraints given by heat source and sink in the Aalborg case study, an alternative hydrogen scenario for the Aalborg case study and electricity input to CHEST from either a wind farm or the grid in the Alpha Ventus case study.

EnergyPLAN model for simulations at national scale

While the TRNSYS and energyPRO models described above were used to simulate a CHEST system under the boundary conditions of a specific case study, simulations at the scale of a national energy system including the use of CHEST were carried out using the EnergyPLAN software. This software works at an aggregated level, i.e. instead of considering each single energy generation plant, a certain technology is represented by a group of plants of the same category, with implemented capacities and conversion efficiencies as input variables. The model is designed to fully model the renewable energy supply for all energy demands at country level with accounting for possible handling of the fluctuation in supply and demand. Hourly balances are calculated for all relevant forms of energy, not only electricity, but also for district heating, cooling, natural gas, hydrogen and e-fuels. By considering these main energy demands of heat, electricity and also mobility, the model allows for studying the cross-sector impacts of CHEST.

Several of such energy system models for EnergyPLAN have been used in the CHESTER project, mainly for a long-term future scenario where the share of renewable energy sources is close to 100%. In some analyses, existing models, developed in other project contexts, have been used, mainly from the Heat Roadmap Europe project [HRE 2018]. For the CHESTER project, an updated model specifically designed for the German energy system at present (2020) and in the future (2050) including several future scenarios was implemented in the EnergyPLAN software to analyze both technical and economic market potential of CHEST integration. The analysis of the technical potential refers to the fundamental imbalances between energy supply and demand and the possible savings in energy consumption given by the use of energy storage technologies. The model gives priority to the energy-efficient production and conversion units in order achieve minimum fuel consumption. In contrast to this, in the analysis of the economic market potential, the objective is to cover the energy demand at the lowest marginal costs of operation.

Simulations were carried out analyzing the CHEST potential for different scenarios concerning the future district heating supply (either dominated by CHP or by HP) and for different approaches of CHEST integrated in the national energy system (either as electricity-only storage or with DH integration). The technical potential of CHEST was evaluated based on calculated amounts of charged and discharged electricity, reduction of primary energy consumption and excess electricity production for the several scenarios and in comparison to a competing storage technology (Li-ion batteries). Economic potential was mainly evaluated based on the determination of economically optimal capacities of HTHP, ORC and HT-TESS as well as the overall market potential for Germany and the EU.

Simple model for web tool application

For the CHEST web tool, which allows any interested user to generate a predesign of a CHEST system and analyze the energetic and economic feasibility when implemented in the user´s current energy system, a simplified Python-based model (calculation engine as the backend of the web tool) was developed. It is suitable for the performance evaluation of two different operation modes: (a) a grid-connected CHEST system participating in the day-ahead and in the balancing electricity market and (b) a stand-alone CHEST system with the main purpose of maximizing the user´s own RES electricity generation from PV and/or wind turbines. The main purpose of the web tool is to allow a potential planner or user to make a first assessment of the technical and economic potential for the integration of a CHEST system into a current or future energy system. The web tool is available via: https://chester.datuma.aiguasol.coop/.

A first functionality of the model is the generation of energy profiles based on the limited inputs made by the web tool user and with the help of some basic equations and assumptions on the temporal distribution. For the calculation of PV and wind electricity generation, the model also uses the PVGIS API [PVGIS] to retrieve PV yield and wind velocity data.

The second functionality of the model is the proper sizing of the main components HTHP, ORC (only necessary for stand-alone systems) and PCM storage (LH-TES), which is done based on electricity demand and deficit profiles (HTHP, ORC) and basic heat transfer and energy balance equations. The efficiencies of the HTHP and ORC are calculated according to a table that considers several fixed points of a performance map for different PCMs and refrigerants with the heat source temperature as the decisive variable of selection for the respective performance map point.

As an output of the model, the main characteristics of the CHEST system and its main components, such as size and efficiency of HTHP, ORC and LH-TES as well as P2P ratio and thermal efficiency of the CHEST system are visualized for the user together with overall energy balances (electrical, thermal) of the energy system including CHEST integration. Furthermore, most important economic figures such as CAPEX, OPEX and total cost of ownership and payback time are calculated to give the web tool user an impression of CHEST´s economic feasibility for the designated use case.

2.3. Main energetic and environmental results

The following subchapters briefly describe what was observed during the CHESTER project about the energetic and environmental performance of the CHEST system. For more detailed results, please refer to the public reports of the project [Del 2023] on the website: https://www.chester-project.eu/public-documents/.

2.3.1. P2P ratio

The roundtrip efficiency or power-to-power ratio (P2P ratio), defined as the ratio between net electricity generation of the ORC and electricity consumption by the HTHP in a certain period (e.g. one year) is perhaps the most important performance parameter of the CHEST system due to its main function as an electrical energy storage and being as such in competition to other storage technologies such as pumped hydro, CAES or batteries. In order to reach a high P2P ratio, the temperature level of the heat source for HTHP evaporation should be as high as possible and the temperature level of the heat sink for ORC condensation should be as low as possible. Furthermore, the compressor and expander efficiencies need to be high, there should be no heat and pressure losses, and a good match between temperature profiles inside the heat exchangers is required to ensure minimum pinch points. However, real CHEST systems will show heat losses in the HT-TESS as well as in the HTHP and ORC cycle, and also exergetic losses in all the heat exchangers, and limited isentropic efficiencies of the HTHP compressor and ORC expander. Thus, it is important to know which P2P ratios can be expected for a CHEST system under certain boundary conditions. In the following, this will be discussed based on the simulation and experimental results of the project.

<u>P2P ratio based on simulation results:</u>

Simulations with the first simple TRNSYS model (see Section 2.2.5) for altogether 5 case studies were carried out with the refrigerants butene or R1233zd(E) and KNO_3-$LiNO_3$ with a melting temperature of 133 °C as the PCM. In these simulations, the CHEST system was coupled with an LTTES, which affects the heat source and sink temperatures, because the extraction of heat from the LTTES and the ORC condensation of heat to the LTTES change the temperatures inside the LTTES. Furthermore, there are limitations concerning the maximum LTTES water temperature and thus concerning the maximum heat source temperature for the HTHP (about 95 °C). Moreover, low ORC condensation temperatures are not realized by condensation to the LTTES, but to the environment. And finally, the RES heat temperatures and the DH network forward and return temperatures also define temperature levels inside the LTTES and therefore the heat source and sink temperatures for the CHEST system.

For the two case studies Aalborg and Alpha Ventus, the P2P ratios were in the range of about 30 - 50%, depending mainly on the HT-TESS and HTHP size. The bigger the HT-TESS and HTHP, the more heat is drawn from the LTTES, which reduces the heat source temperature and thus the COP and finally the P2P ratio, whereas the ORC efficiency is only slightly increased by the increase of ORC operation and reduction of heat sink temperature. The refrigerant R1233zd(E) was found to show slightly (about 4 - 7%) higher P2P ratios compared to butene. Given the fact that thermal losses are not even accounted for in this TRNSYS model, the P2P ratios for these two case studies must be evaluated as relatively low.

For the three other case studies Turin, Ispaster and Barcelona, the possibility of ORC condensation to the environment was added to the TRNSYS model, which increases the ORC efficiency. In the case study Turin, this together with quite high DH network return temperatures of about 70 °C leading to high LTTES temperatures and thus COPs results in P2P ratios of about 60 - 65% for butene as the refrigerant. For Ispaster, the DH network return temperature of 55 °C results in P2P ratios of about 45 - 55% when ORC condensation to the environment is carried out. In the case study Barcelona, ORC condensation is conducted either to the environment or to the LTTES or partly to the one or the other heat sink, depending on the size of the HTHP. For larger HTHP sizes with a high amount of heat drawn from the LTTES, the P2P ratio is in the range 30 - 40%, whereas for very small HTHPs, the P2P ratio can reach 60% and beyond. These results show that ORC condensation to the environment increases the P2P ratio. However, on the other hand, heat is dissipated by this measure.

The simulations carried out with the advanced TRNSYS model (see Section 2.2.5) aimed at analyzing different refrigerant/PCM combinations as well as (constant) temperature levels of heat source and heat sink (no coupling to an LTTES). The results show that P2P ratios > 100% are achievable for several refrigerant/PCM combinations, such as cyclopentane and $LiNO_3$-$NaNO_3$-KCl with a melting temperature of 160 °C. However, such high P2P ratios inevitably mean a net heat requirement, see Section 2.3.2.

Simulations carried out with the steady-state EES model (see Section 2.2.5) aimed at showing the potential thermodynamic performance of a CHEST system at the MW scale under different boundary conditions, i.e. for different refrigerants and PCMs as well as for different HTHP heat source and ORC heat sink temperatures. Using one and the same refrigerant for both the HTHP and ORC cycle and a PCM with a melting temperature of 133 °C, R1233zd(E) showed the highest P2P ratio of 86% under nominal operating conditions (HTHP heat source temperature of 80 °C, ORC heat sink temperature of 25 °C). For the same operating conditions and the same PCM, an even higher P2P ratio is achieved when using R1233zd(E) as the working fluid for the HTHP cycle and butene as the working fluid for the ORC cycle [Has 2020].

Simulations with the steady-state EES model were also carried out for a CHEST system at the kW scale and based on estimated efficiencies for the compressor and expander. Using R1233zd(E) as the working fluid for both the HTHP and ORC resulted in a roundtrip efficiency of 74% for a HTHP heat source temperature of 100 °C and an ORC heat sink temperature of 25 °C [Has 2019].

<u>P2P ratio based on experimental results:</u>

The round-trip efficiency of the CHESTER laboratory prototype is estimated for combinations of average, maximum and minimum operating conditions of the HTHP, ORC and HT-TESS. The HTHP and ORC are not operated at the same time, and in each of the tests, different parameters were analyzed, so that a set full system efficiency for this prototype system cannot be calculated. The calculated roundtrip efficiencies, defined by the product of the efficiencies of the main components HTHP, HT-TESS and ORC, are in the range of 17.9% to 37.2%. For each of the system parts, efficiency could be increased through better thermal insulation and optimization of components through the lessons learned and technical developments throughout the project. Estimations for future systems based on the current prototypes and optimizations that are deemed significant and feasible, roundtrip efficiencies in the range of 68% would be attainable. Details on this future efficiency are discussed in Section 7.3.

The net power ratio was calculated including ramp-up and ramp-down phases, during which many system inefficiencies occur. This was calculated at about 20%. This ratio is calculated for the limited number of full-cycle tests, each conducted at different parameters.

<u>Overall conclusion:</u>

The real laboratory (small size) CHEST system has shown considerably lower P2P ratios than the simulation results for a real scale CHEST system, as it was expected. This is mainly due to the limited compressor and expander efficiencies due to their small size, as well as heat losses in these components due to the need for accessibility and visibility of components in the prototype.

The highest losses are found to arise in the HTHP: For HTHPs at the kW scale, the isentropic efficiencies are estimated to be about 92%, with heat losses of 40 % resulting in overall compressor efficiencies of about 55%. For HTHPs at the MW scale, the isentropic efficiency will be slightly higher (93%) and the heat losses considerably lower (20 - 25%) resulting in overall compressor efficiencies of 70 - 75%.

Up-scaling and identified optimizations (cf. Section 3) lead to think that P2P ratios in the range of 68% could be achieved applying current prototype designs (i.e. using a passive latent heat energy storage concept and the same temperature levels for the heat source of the HTHP, the melting point of the PCM and the heat sink of the ORC) at large scale. In addition to the specific design of the individual technologies and the selected working fluids and the PCM used in the prototype, simulations have been performed for different combinations of working fluids and PCMs as well as design specifications. As the simulations have shown, theoretically, P2P ratios of > 100% can be achieved at certain conditions. This requires a suitable refrigerant/PCM combination, specific HTHP and ORC designs maximizing the individual efficiencies, high HTHP source and low ORC sink temperatures.

2.3.2. Electricity vs. heat

From a theoretical point of view, it is clearly difficult to maximize both the heat and electricity output of the CHEST system, since the energy output (heat and electricity) of the system is limited to be at most the energy input (heat and electricity) in an ideal system without losses. Thus, increasing either heat or electricity output will lead to a decrease of the other output. And due to the various sources of losses – limited isentropic efficiencies of compressor and expander, exergetic losses during heat transfer in the heat exchangers, dissipated ORC condensation heat due to missing heat demand or heat demand at a too high temperature level, thermal losses of the storage system and connecting components – it has been shown through the simulations and experiments that even for P2P ratios far less than 100%, a CHEST system can be a net heat consumer.

This competition between electricity and heat storage service requires a proper adaption of the CHEST system to the desired kind of application. As has been discussed above, CHEST offers several possibilities to shift its output towards electricity or towards heat. On the one hand, this can be realized by a suitable combination of refrigerant and PCM. On the other hand, the ratio of electricity and heat output can be controlled by the adaption of the heat source and sink temperatures, for instance, by delivering the ORC condensation heat towards the environment instead of delivering it to a DH network or a thermal energy storage.

However, it has become clear that due to this inverse relationship between electrical and thermal performance, CHEST cannot maximize electricity and heat service at the same time. In general, it can be concluded that the higher the electrical output of the CHEST system, the more heat it requires. Thus, for CHEST systems with a desired high electrical output and in this case probably being a net heat consumer, highly available as well as cheap low temperature heat sources such as waste heat or excess solar heat should be used.

This important outcome of the analyses has a strong impact on the (economic) feasibility of CHEST in different applications, see Sections 7.5 and 8.

2.3.3. Environmental performance of CHEST system

The results from the life cycle analysis (LCA) show that the environmental performance of CHEST is currently rather low, which is mainly due to the PCM and the heat exchanger design used in the prototype, but this cannot be generalized for CHEST systems as such. The analysis for the prototype design showed that even on the long term and accounting for the benefits that occur due to enabling RES integration and the reduction of other primary energy sources, the emissions avoided do not compensate for the environmental impact caused by the production and end of life of CHEST components. This is mainly due to the high environmental footprint of the HT-TESS, in particular of the currently used PCM and the heat exchanger design. As a result, CHEST does not show an environmental payback within its lifetime given the design that was chosen for the prototype. It must be said that in this analysis, no recycling or reuse of the PCM was considered, which could in principle be possible.

However, an additional analysis shows that when eliminating the PCM and reducing the weight of the metal parts, CHEST becomes a competitive solution in terms of environmental impact reduction. This means that CHEST indeed has potential in terms of environmental impact reduction. Furthermore, the analysis shows where to focus the improvement efforts.

The LCA also shows that CHEST deployment is particularly interesting when the integration with a DH network is possible. A CHEST system used as electricity-only storage, on the other hand, gives positive environmental results only under very specific boundary conditions. Again, this statement is valid for the prototype design and in particular for the PCM used, but it is not generally true for future real-size CHEST systems, because the use of other PCMs and other heat exchanger designs can considerably change the environmental footprint.

The overall conclusion of the LCA is that CHEST in principle has the potential to be an environmentally friendly storage solution. However, in order to realize this, clearly, further research especially on the overall HT-TESS concept and the used materials is required.

2.4. Main economic results

The following subchapters briefly describe the major outcome of the economic analyses carried out within the CHESTER project. For more detailed results, please refer to the public reports of the project [Del 2023] on the website: https://www.chester-project.eu/public-documents/.

2.4.1. General boundary conditions

The general boundary conditions for the CHEST technology were analyzed with the help of a PESTEL analysis and a Porter analysis for five selected European countries represented in the Consortium of the CHESTER project (Spain, Denmark, Germany, Belgium and the Netherlands). As an overall conclusion, there is a common goal of decarbonization and increasing the contribution of RES in the electricity sector across the European countries analyzed, despite very different shares of renewables currently integrated. Furthermore, an increase in the energy demand and an increase in the (fluctuating) RES electricity curtailment are expected in the coming years. Beside the extension or reinforcement of transmission and distribution grids being an expensive and not a definitive solution, electrical energy storage (EES) is a suitable solution for ensuring the reliability of the electrical grid. There is limited implementation of EES at the moment, mainly due to technical and economic reasons, but given the expected developments described above, EES will presumably increase rapidly in the coming years.

In this field of electrical energy storage, CHEST faces a range of competing technologies (for more about this, see Section 6) in a very dynamic market with recent and certainly also future development of new technologies, especially with respect to electrochemical EES (batteries). However, the different technologies can address different electrical services due to their specific characteristics, such as response time, capacity, efficiency, and costs.

The power of customers in the EES market is fairly strong due to the large variety of EES technologies and due to the fact that the product sold (energy storage) is not special, but a commodity. As stated above, the EES technologies with their specific characteristics qualify them for different electrical services, but still, there is a certain choice to make for a given service. Some of CHEST´s competitors such as PHS and CAES might be excluded at a certain site, due to geographical or environmental restrictions, but finally, investment and operation costs will be of key significance in the decision for or against CHEST, in particular when compared to batteries.

The power of suppliers for CHEST components can also be evaluated as fairly strong since there is currently a limited number of manufacturers for heat pumps (or compressors as the main part) with this unusually high temperature level and for ORCs (or expanders as the main part) with very specific requirements. For the HT-TESS, latent heat thermal energy storage systems of the designated dimension are in an early stage of development. The same is true for the IE engine pump, which is currently in the prototype phase and thus not a standard component.

The regulatory framework on EES technologies was found to be an essential aspect to consider for the deployment of EES. The regulatory situation is not always clear and can be unfavorable, for instance regarding possible double taxation. For participation in the reserve markets, stringent requirements for instance concerning response time and minimum offered power or capacity mean obstacles for the entry into these markets.

Since CHEST is not only an EES technology, but combines the electricity and the heat sector due to its heat requirement and heat supply, the heating sector was also analyzed for the 5 European countries mentioned above. In particular, the presence of DH networks (as a possible heat sink for CHEST) was analyzed (rather low e.g. for Spain and rather high for Denmark), which offers further opportunities for CHEST. As a type of thermal energy storage, CHEST has certainly many competitors, such as hot water, pit thermal energy storage, molten salt, and rock storage. However, as was indicated in Section 2.3.2 on the issue of electricity vs. heat output and will be discussed more in detail in Sections 7 and 8, heat services might have a lower relevance in the application of CHEST compared to electrical services, but are nevertheless expected to be important for an economic viability of CHEST.

2.4.2. Economic performance of CHEST

In the CHESTER project, several applications and dedicated business models were studied, mainly through simulative analysis:

- CHEST as an electricity storage for the balancing of electricity surplus and deficit in a (national) electricity grid → business model given by:
  - economic benefit through the participation in different electricity markets, e.g. day-ahead market (DAM) and restoration reserve (RR) market
  - economic benefit through (investment) cost savings, i.e. CHEST as a cheaper alternative compared to other electricity storage solutions such as pumped hydro or compared to investments in the grid reinforcement
- CHEST as an electricity storage in connection with a renewable electricity generator such as a wind farm → business model given by the reduction of curtailment and shift of electricity generation to times with higher electricity prices
- CHEST as an electricity and heat storage in a (local) energy system, which can be an energy community, an industrial park or any other location with electricity and heat demand as well as electricity and heat generation → business model given by the reduction of overall energy costs for the stakeholders in this energy system

<u>Participation in electricity markets:</u>

A first business case that was intensively studied in several tasks of the project under different boundary conditions is the participation of CHEST in the spot (DAM) and/or tertiary regulation (RR) electricity market. Arbitrage operation of CHEST, i.e. using the electricity price fluctuations of the spot market, was found to be not economically viable. The current very low price fluctuations in this market mean few hours of operation and low revenues, compared to the high investment costs of the system. Taxes and fees as well as the operating costs further reduce the revenues. For higher price fluctuations, as is forecasted for 2030 and 2040, revenues increase, but this business case stays unprofitable. The combined operation of CHEST in both the spot and tertiary regulation market (i.e. in the course of a year, CHEST sometimes participates in the one and sometimes in the other market, but not in both of them simultaneously) increases the revenues significantly compared to the case of operation in the spot market only. However, due to relatively rare times with favorable prices in the regulation market, the investment costs cannot be covered by the annual profits within an acceptable payback time.

The analysis of this business model of the participation of CHEST in the spot and/or tertiary regulation market was carried out for Danish markets and taxation regulations (Aalborg case study). In Denmark, there is almost no availability payment in the tertiary regulation market (price paid for making a certain regulating power available), but only energy payment (price for the actually consumed or delivered regulating electricity). The analysis was also carried out for Germany (Alpha Ventus case study), with existent availability payments for both positive and negative regulating power, but the overall conclusion on the profitability is the same as for Denmark [Star2020] [Star 2021].

Furthermore, different control strategies concerning optimization of charging and discharging and the proper selection of one of the two markets at a certain point of time were applied. This showed the potential for increasing revenues, but also did not change the overall conclusion on this business case.

<u>CHEST vs. alternative EES solutions:</u>

The comparison of CHEST with alternatives for balancing grid electricity surplus and deficit also showed quite difficult business opportunities for CHEST, at least under the current boundary conditions.

Compared with the use of pumped hydro storage (PHS), CHEST had, in most cases, a lower economic performance. However, both technologies did not give a payback within their lifetime actually, which illustrates the generally difficult economic conditions for EES technologies. In this analysis, the typical operation on an annual base of a PHS was compared with the power-to-power operation of CHEST under different techno-economic scenarios and adopting different operating logics. Although the net profit of the CHEST system exceeds the value of PHS in some logics, the internal rate of return (IRR) is higher in case of PHS.

The CHEST system was also assessed as a power-to-power system to shift renewable electricity overproduction, hence avoiding curtailment and possible bottlenecks and critical events on congested portions of the electric grid. The economic viability was compared with the option of grid reinforcement. When the grid experiences massive limitation on the amount of energy that can be dispatched without any issue, the CHEST system may play a pivotal role in the correct management of energy fluxes. The high costs of CHEST components represent an important penalty for the CAPEX of the system. This means that grid reinforcement will mostly be the economically more favorable option. However, the expected market evolution of CHEST components and the improved scale economies of such power-to-heat-to-power systems will imply a dramatic reduction of the initial investment costs. The CHEST system starts to be more competitive in contexts with a heavy penetration of small-size non-programmable renewable plants (< 10 MW) that are not close to the transmission grid.

For the Danish case study of Aalborg, an alternative storage scenario with a hydrogen plant that consisted of a hydrogen production unit, a hydrogen storage and a hydrogen fuel cell was also analyzed. Here, the CHEST system showed a better techno-economic performance compared to the hydrogen technology. Despite the lower investment costs for the hydrogen system, the expected revenues were lower by 20 - 30%, and the operating expenses were up to 3.5 times higher compared to the CHEST case.

<u>CHEST in connection with renewable electricity generators:</u>

This business case was studied with the example of a case study with the German offshore wind farm Alpha Ventus and a CHEST system installed behind-the-meter that is supposed to reduce curtailment of the wind turbines and shift the supply of generated electricity to the grid to hours of higher electricity prices. The electricity prices in this case were assumed to be the ones from the German intraday electricity market. Different situations concerning possible grid constraints and thus wind turbine curtailment in the case without CHEST were taken into consideration.

The results of this case study showed that CHEST increases the value of the generated wind power and thus the annual profit. However, this benefit did not compensate for the high investment costs, which means that installing no CHEST system was the economically more favorable option under current boundary conditions.

CHEST as electricity and heat storage in a local energy system:

Another major business case that was intensively studied in the CHESTER project is the application of CHEST in a local energy system with the main purpose of increasing locally generated PV electricity and by this, reducing the purchase of electricity from the grid. This business case was studied with the example of the small Spanish town Ispaster, with different boundary conditions concerning local energy generation (PV, solar thermal, biomass) and also for analyzing CHEST in an island energy system without any grid electricity access. In this business case, CHEST was compared to batteries as an alternative storage solution.

As a main conclusion, CHEST was found to be competitive and in some cases even an economically favorable storage solution compared to the batteries. However, this strongly depends on the type of battery (e.g. lead-acid or Li-ion), the battery investment costs and assumed life times. Furthermore, electricity storage – no matter if it is CHEST or batteries – was found to be unprofitable in general, i.e. it is always cheaper not to install EES technology and continue purchasing electricity from the grid. This is due to the generally high investment costs of EES, which cannot be compensated by the savings resulting from the reduced grid electricity purchase.

An advantage of the batteries compared to CHEST in this case study is the fact that batteries do not affect the heat balance. In contrast to that, the CHEST system requires heat and faces the conflict of electricity vs. heat output maximization (see Section 2.3.2). When choosing conditions in favor of a high P2P ratio and thus for higher savings of grid electricity, this increases the net heat demand and by this also the demand for purchase of e.g. biomass.

Furthermore, the economic viability of a CHEST application as an electricity and heat storage was studied with the example of a Danish industrial park. In this case study, the several industrial companies have both heat demand and available waste heat to different extents and the same is true for electricity demand and generation. Instead of using a nearby DH system for covering the heat demand and wasting surplus heat e.g. with the help of dry coolers, a CHEST system can be used for the exchange of heat among the several industrial companies.

The analysis of this business case shows that there seems to be an interesting opportunity for all partners involved in the CHEST scenario, since all of them get a return on investment within several years, and considerable savings compared with the reference scenario of the DH system connection. This business case is more profitable to the industrial companies with waste heat, because most of the CHEST investment (including a significant part of the district heating network pipes investment) is covered by the industrial companies with a heat demand. However, also this analysis showed that the business case is strongly dependent on the boundary conditions, here in particular the CAPEX of CHEST and the number of operating hours of CHEST, which beside the configuration and size of the CHEST components depends on the electricity and heat generation and demand profiles of the industrial companies.

3. Identification of required technological progress

3.1. Main objectives

As was explained in the previous sections, the CHEST technology was lifted from TRL 3 to 5 in the CHESTER research project by the development, build and test of a first-of-its-kind prototype as well as accompanying comprehensive theoretical work. Two major issues that can be strongly improved by technological progress were identified:

- **Reduction of CAPEX**. The analysis on the economic performance of CHEST (see Section 2.4.2) clearly showed that CHEST generates economic benefit by either revenues at for instance the electricity markets or through savings in the energy bill. However, in most cases, this cannot compensate for the significant amount of CAPEX resulting in unprofitable business cases. Thus, in order to achieve economic viability, investment costs (CAPEX) of the CHEST system have to be reduced considerably.
- **Increase of efficiencies**. Simulations have shown that quite high efficiencies of the complete CHEST system (P2P ratio) are possible. The COP of the HTHP and the electrical efficiency of the ORC are the most important parameters towards maximizing the overall system efficiency. Technological improvements that allow for reaching higher efficiencies in the power-to-heat and heat-to-power conversions will be necessary in order to achieve satisfying energetic, environmental and economic performance.

Based on the results of the project and the expertise of the respective partners, a range of measures and approaches for technological progress – both at the system and component level – were identified through dedicated discussions among the project partners. The realization of this identified technological progress, which is explained more in detail in the following sections, has the potential of boosting the CHEST technology significantly in terms of the abovementioned main objectives. To which extent exactly the partners think reduction of CAPEX and increase of efficiencies can be realized is given in Section 7.3 in the key messages.

3.2. Technological progress at the system level

3.2.1. Scale-up of the CHEST system

As was mentioned above, the prototype that was developed, built and tested in the CHESTER research project has an electrical charging and discharging power of about 10 kW_{el}. This is much smaller than real-size commercial CHEST systems are thought to be in the future. In particular, because of the main objectives mentioned above, i.e. satisfying efficiencies at low CAPEX using economies of scale, a typical commercial CHEST system should have a charging and discharging power of several MW_{el}. Actually, the rather low efficiencies of the prototype are at least partly due to its small size, since HTHP and ORC at MW-scale use different, more efficient technologies (see below). However, it is not useful to build a MW-scale system for the objective of demonstrating the operation of a first-of-its-kind prototype. That is why the prototype had a size of only 10 kW_{el}, which inevitably leads to some reductions in the efficiencies of the HTHP and the ORC compared to what can actually be expected for these components even at current state of the technology.

The necessary scale-up of the CHEST system is mostly related to the scale-up of its main components. While for the HTHP and the ORC, there is in principle the proven turbomachinery technology available, the scale-up of the HT-TESS is much more challenging, since there is no experience in particular on such a large PCM storage to date.

However, due to the quite complex concept of a CHEST system, the scale-up of the system is not just achieved by the mere scale-up of its main components HTHP, ORC and HT-TESS. In a CHEST system, in order to achieve high system performance, it is crucial that the operation of the components matches one another. To mention just two examples here that are relevant for the CHEST system performance: the ratio of latent to sensible heat from the HTHP to the HT-TESS should match the ratio of latent to sensible heat from the HT-TESS to the ORC, and the temperature levels and temperature differences in the various heat exchangers need to be well adapted in order to minimize exergetic losses. These and other performance determining issues depend on a range of constructional as well as operational parameters of the components and at the system level.

3.2.2. Simplification of the CHEST concept

The abovementioned scale-up of the CHEST system is expected to both reduce CAPEX and improve the efficiency of the CHEST system significantly. A further considerable potential for the reduction of CAPEX is seen in the simplification of the CHEST concept. The following different possibilities for a simplification were identified.

<u>Use of the same refrigerant for HTHP and ORC:</u>

As was mentioned in Sections 2.1.1 and 2.1.2, the HTHP and the ORC of the prototype use different refrigerants, R1233zd(E) and R1336mzz(E), respectively. The two systems, in addition, use different lubricants. This may have been reasonable for the two individual components, but has one major disadvantage for the LH-TES: In order to avoid the refrigerants mixing or getting into the wrong components, there have to be two separate circuits for the HTHP and ORC refrigerant in the LH-TES, or a dividing middle circuit with a simple LH-TES but increased temperature gradients in the system. To reduce temperature gradients, a dual-tube design for the heat exchanger in the LH-TES as is shown in Figure 2 is used.

Using one and the same refrigerant for both HTHP and ORC would enable a single-tube design, which is simpler, saves material (steel for the tubes and probably also some aluminum for the fins) and manufacturing costs (welding). A positive side effect of this would be the increase of the ratio of PCM to HX volume in the LH-TES. This also decreases the overall size of the LH-TES.

Figure 2: Dual-tube HX design for the separation of HTHP and ORC refrigerant used inside the LH-TES (Source: DLR).

However, one technological challenge to be solved in this context is to avoid migration of refrigerant and lubricant of the compressor and expander. The control mechanisms for a connected system would also need to be developed, as the systems operate at differing temperature and pressure levels.

<u>Combined HTHP-ORC-component:</u>

The construction of a combined HTHP-ORC-component has a huge potential for the reduction of CAPEX. Using the same refrigerant for the HTHP and the ORC is a prerequisite for this, but as was shown above, this would be advantageous in any case. In a first step, the heat exchangers with the LH-TES and the SH-TESS as well as parts of the piping could be used for both HTHP and ORC, but there would still be a separate compressor and expander. A further simplification would be a single reversible system for the HTHP and ORC, i.e. compressor and expander are one and the same component.

The combined use of components for the heat pump and the power cycle is a relevant challenge for other power-to-heat-to-power systems as well, so-called “Carnot batteries” as the following two examples illustrate. Figure 3 shows a schematic drawing of the heat pump cycle (left) and the power cycle (right) of the power-to-heat-to-power system of the company Echogen [Ech 2023]. This system uses CO_2 as the refrigerant for the two cycles between a hot and a cold reservoir, each of them designed as a two-tank-system. As can be seen from the figure, the three heat exchangers are used in both the heat pump and the power cycle. Furthermore, there is obviously a component acting as a compressor for taking up electricity (“Echg”) in the heat pump cycle and acting as a turbine for the generation of electricity (“Egen”) in the power cycle. However, there are still some components that are separate for the two cycles, e.g. the pump in the power cycle, which is replaced by the turbine for recovering some of the electricity required in the heat pump cycle.

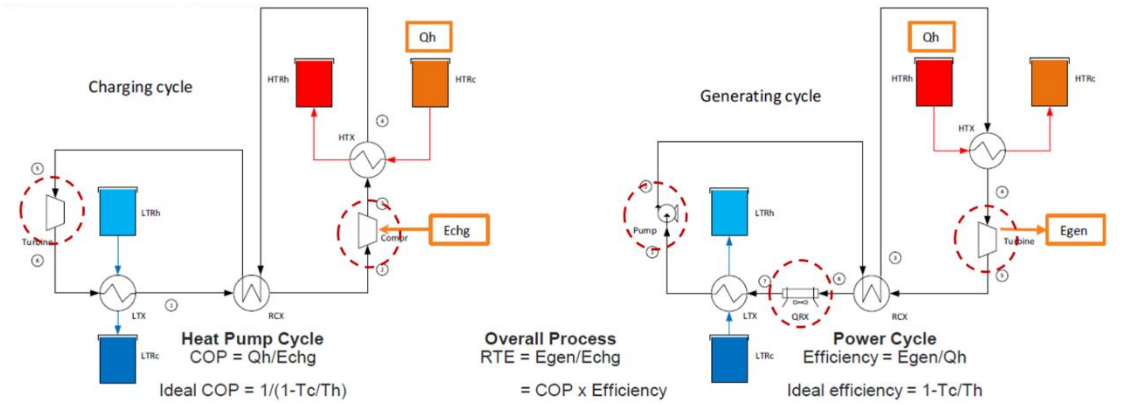

Figure 3: Schematic of the heat pump and power cycle in the power-to-heat-to-power system from Echogen (Source: Echogen power systems [Ech 2023]).

Figure 4 shows a schematic drawing of the power-to-heat-to-power system of the company MAN [MAN 2020], which also uses CO_2 as the refrigerant. In this system, there is a separate compressor (1) and expander (2), but the two heat exchangers (3) and (4) are used for both the heat pump and the power cycle.

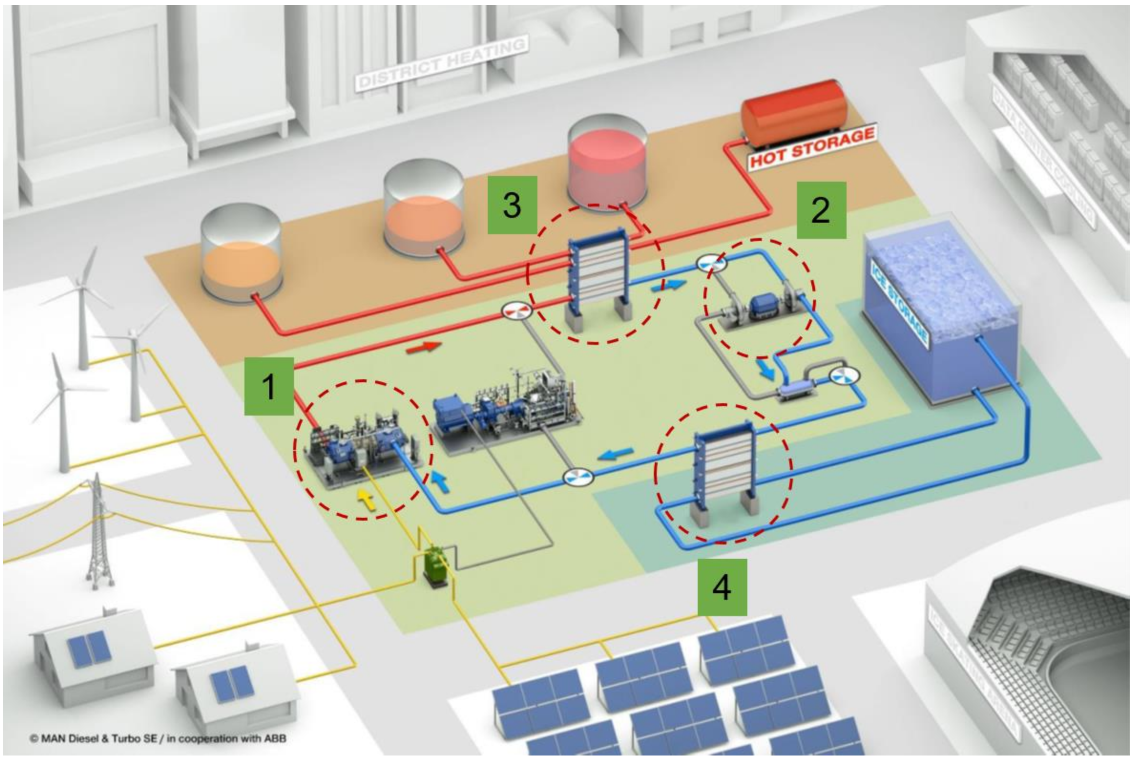

Figure 4: Schematic of the heat pump and power cycle in the power-to-heat-to-power system from MAN (Source: MAN [MAN 2020]).

The two examples clearly show that it is possible to combine the heat pump and the power cycle in an infrastructure where heat exchangers, pipes, valves and other parts are used for both cycles.

One-storage-concept:

The current concept of the HT-TESS is quite complex, since it uses the combination of a latent heat thermal energy storage and a sensible heat thermal energy storage, which in turn is a two-tank storage system. This requires respective heat exchangers and there is also the need to match the ratio between latent and sensible heat between charging and discharging operation. This complexity is fully comprehensible from an efficiency point of view, since a latent and a sensible storage part lead to low temperature differences in the heat exchangers and thus a good exergetic efficiency. However, it makes the storage system costly and its operation more complicated.

In contrast to that, a concept with only one storage – either sensible or latent, but in particular only sensible with water as the storage medium – would simplify the storage system substantially. Beside the storages, this would also reduce the number of further components such as the HTHP subcooler and the ORC preheater. Thus, such a one-storage-concept is thought to reduce CAPEX considerably, in particular, if no costly PCM is used, but just a pressurized hot water storage. The use of water as the storage medium would also be beneficial from an environmental point of view. However, it must be very clearly said that this CAPEX reduction inevitably comes along with a decrease in the overall efficiency of the CHEST system. Furthermore, CHEST would lose one of its key and actually CHEST-defining features as is discussed more in detail in Section 7.6 in the key messages.

3.2.3. System control

System control is related to two different issues in this context. On the one hand, it means the optimization of settings such as temperatures, mass flows and ramp-up and shutdown procedures, and this aims at the increase of the efficiency of the components and the complete system. With the build and test of the CHESTER prototype, first experiences with this were made, but it clearly needs further improvement.

On the other hand, system control means a control at a higher level focusing on the increase of the operation time in order to increase CHEST´s annual revenues. This means, based on the (dynamic) external boundary conditions given by heat and electricity prices, weather conditions, heat and electricity generation and demand profiles, tax regulations, etc., this superordinate control is to determine when the HTHP and ORC operate and at which power. This should be done in an intelligent way, i.e. considering all relevant abovementioned boundary conditions, including also, for instance, a forecast of electricity prices and weather conditions.

Figure 5 shows the schematic illustration of a Smart Energy Management System (SEMS) that was developed in the CHESTER project. This is a set of different tools and modules using external data (boundary conditions), a simulation of the system (CHEST model) and an optimizer to find an operation strategy that dynamically maximizes the economic performance of the CHEST system.

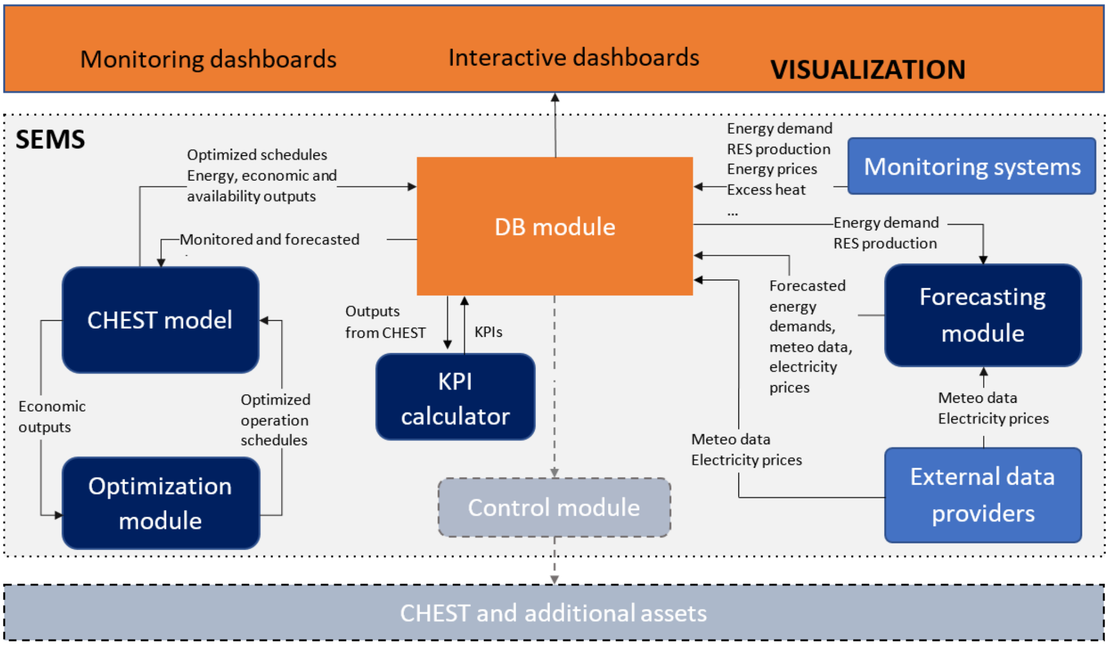

Figure 5: Schematic of the Smart Energy Management System (SEMS) developed in the CHESTER project (Source: Aiguasol).

The analysis of the SEMS shows that it does not always find the best operation strategy currently, and thus requires some improvement, for instance concerning the proper forecast of electricity prices, but also in terms of giving the state of charge (SoC) of the LH-TES a higher significance in order to avoid that the HTHP and ORC operation are blocked by a completely discharged or charged LH-TES, respectively. However, the analysis also showed the potential of the increase of CHEST´s annual revenues by defining a respective control strategy. Thus, the further development of the SEMS is a suitable means to improve the economic viability of CHEST.

3.3. Technological progress at the component level

3.3.1. HTHP

Two major improvement measures for the HTHP have already been mentioned above, namely:

- the use of turbomachinery that goes along the scale-up of the HTHP to MW size and mainly aims at increasing its efficiency, see Section 3.2.1
- the combination with the ORC cycle, which mainly aims at reducing CAPEX, see Section 3.2.2

Beside these two measures, the following required technological progress for the HTHP was identified:

Higher condensing (heat sink) temperatures:

In order to melt the PCM used in the CHESTER prototype, the HTHP has to deliver a condensing temperature slightly above the melting temperature of the PCM (here, 133 °C). As was mentioned in Section 2.1.1, the HTHP used in the CHESTER prototype achieved a maximum condensing temperature of 148 °C in experimental testing.

Going for higher condensing temperatures could be useful, which is mainly a consequence of the objective to use alternative PCMs (with higher melting temperatures) in the LH-TES that are cheaper and/or have a lower environmental footprint compared to the PCM that was used in the CHESTER prototype. On the other hand, higher condensing temperatures of the HTHP will lead to a decrease of the COP assuming that the heat source temperature of the HTHP is kept constant.

The main technological challenge here is to develop turbocompressors that are able to realize such higher condensing temperatures while keeping the COP as highest as possible and minimizing heat losses as well as exergetic losses in the heat exchangers. Currently, there are very few (commercial) products available that exceed condensing temperatures of 148 °C. The maximum temperatures that are currently achieved (but rather at a prototype status) are in the range of 160 °C [Arp 2018] and up to 180 °C [Bel 2021].

Decrease of ramp-up time:

The ramp-up time for the HTHP that is currently achieved accounts for about 5 min. "Ramp-up time" in this context means the start of the HTHP with already heated fluid inside the circuit until the designated electrical power is reached. A "cold start", i.e. including the heating of the fluid inside the circuit, takes some minutes longer.

A ramp-up time of about 5 min is already quite fast, but together with the ramp-up time of the ORC, see Section 3.3.2, still excludes CHEST from some applications such as the secondary regulation market. This secondary regulation market promises higher revenues than e.g. day-ahead or tertiary regulation market. So, clearly, it would be beneficial to develop a HTHP with a ramp-up time of < 5 min in order to extend CHEST´s possible applications and increase its economic viability. This can mainly be achieved by the development of respective compressors, but also through improvements in the HTHP and overall CHEST control.

Alternative refrigerants:

Further progress on the HTHP can also be made through the use of alternative refrigerants, for instance in terms of the reduction of its environmental impact. R1233zd(E), which was used in the CHESTER prototype, has a very low ODP. However, it is not zero. An alternative with zero ODP could for instance be cyclopentane, which is also more suitable for the abovementioned objective of realizing higher condensing temperatures, since cyclopentane has a critical temperature of 239 °C compared to only 166 °C for R1233zd(E).

3.3.2. ORC

Two major improvement measures for the ORC have already been mentioned above, namely:

- the use of turbomachinery (which is standard in ORC technology, but could not be used in the CHESTER prototype) that goes along the scale-up of the ORC to MW size and mainly aims at increasing its efficiency, see Section 3.2.1
- the combination with the HTHP cycle, which mainly aims at reducing CAPEX, see Section 3.2.2

Beside these two measures, the following required technological progress for the ORC was identified:

<u>Higher evaporating (heat source) temperatures:</u>

Higher evaporating temperatures allow to go to higher HT-TESS temperatures leading to an increase of the cycle efficiency and the generated electricity of the ORC if the heat sink temperature is kept constant. For ORCs, heat source (turbine inlet) temperatures of more than 300 °C are standard technology and manufacturers have experience with a wide range of working fluids [Turbo 2021] [Quo 2013].

<u>Decrease of ramp-up time:</u>

As with the HTHP, the ramp-up time of the ORC should also be reduced. “Ramp-up time” in this context means the start of the ORC with already heated fluid inside the circuit until the designated electrical power is reached. A “cold start”, i.e. including the heating of the fluid inside the circuit, takes some minutes longer.

The ramp-up time for the ORC that is currently achieved with the prototype accounts for about 15 min and thus is considerably longer than for the HTHP. In order to be able to, for instance, participate in the secondary regulation market, a ramp-up time of < 5 min should be achieved. This can mainly be achieved by the development of respective expanders, but also through improvements in the ORC and CHEST system control.

<u>Alternative refrigerants:</u>

The refrigerant that was used in the CHESTER prototype, R1336mzz(E), has zero ODP and a very low GWP of only 2, thus a very good environmental performance. However, it could be reasonable to use alternatives such as cyclopentane because of its higher critical temperature of 239°C compared to 171°C for R1336mzz(E), in order to be able to realize higher evaporating temperatures and thus also higher cycle efficiencies.

3.3.3. HT-TESS

The HT-TESS is a complex storage system with a high CAPEX, in particular because of the LH-TES. So, as was explained in Section 3.2.2, a simplification of the HT-TESS in the form of realizing a one storage concept would considerably reduce CAPEX, but would also reduce the efficiency of the CHEST system. However, also several essential measures for technological progress of the HT-TESS were identified that leave the basic storage concept as it is with the LH-TES and the two-tank SH-TESS system. This is explained more in detail in the following.

<u>Use of alternative PCMs:</u>

The eutectic mixture of potassium and lithium nitrate KNO_3-$LiNO_3$ that was used as the PCM in the CHESTER prototype shows two major drawbacks: first of all, it is relatively costly and furthermore, its high environmental footprint was the main reason for the poor environmental performance of the CHEST system observed in the LCA, see Section 2.3.3. Therefore, it is essential to look for alternative PCMs that are cheaper and have a lower environmental footprint. Further properties to consider in the selection of a PCM are, for instance, the cyclic stability, the phase change enthalpy and the thermal conductivity in the solid and liquid state.

Figure 6 shows a number of phase change materials in the melting temperature range of 100 - 300 °C with their phase change enthalpies, separated into different kinds of PCM. Some promising candidates with a similar melting temperature as the currently used KNO_3-$LiNO_3$ (ϑ_m = 133 °C) were identified: HDPE with only a slightly lower phase change enthalpy, but a considerably lower price; Sebacic Acide, Succinic Anhydride and Acetanilide with a higher phase change enthalpy (price unknown). Other PCMs with even higher phase change enthalpies such as Galactitol, Urea or D-Mannitol are known to be cyclically unstable in air, which makes their handling difficult for use in such a PCM storage. In terms of stability, more promising candidates are inorganic PCMs at higher melting temperatures. For some of these inorganic PCMs such as sodium nitrate ($NaNO_3$) with a melting temperature of 305 °C, there is already some experience with its use in PCM storage for long storage duration design [Joh 2017], and in a storage of at least several hundred kWh size [Lai 2012]. Another well understood candidate is a eutectic of potassium nitrate and sodium nitrate, KNO_3-$NaNO_3$, with a melting temperature of 222 °C [Joh 2015]. So, with the increase of the melting temperature, the probability should be higher to find a suitable PCM that fulfills most of the requirements such as high stability, low price and environmental footprint, etc. However, in general, more information is needed about their properties and behavior.

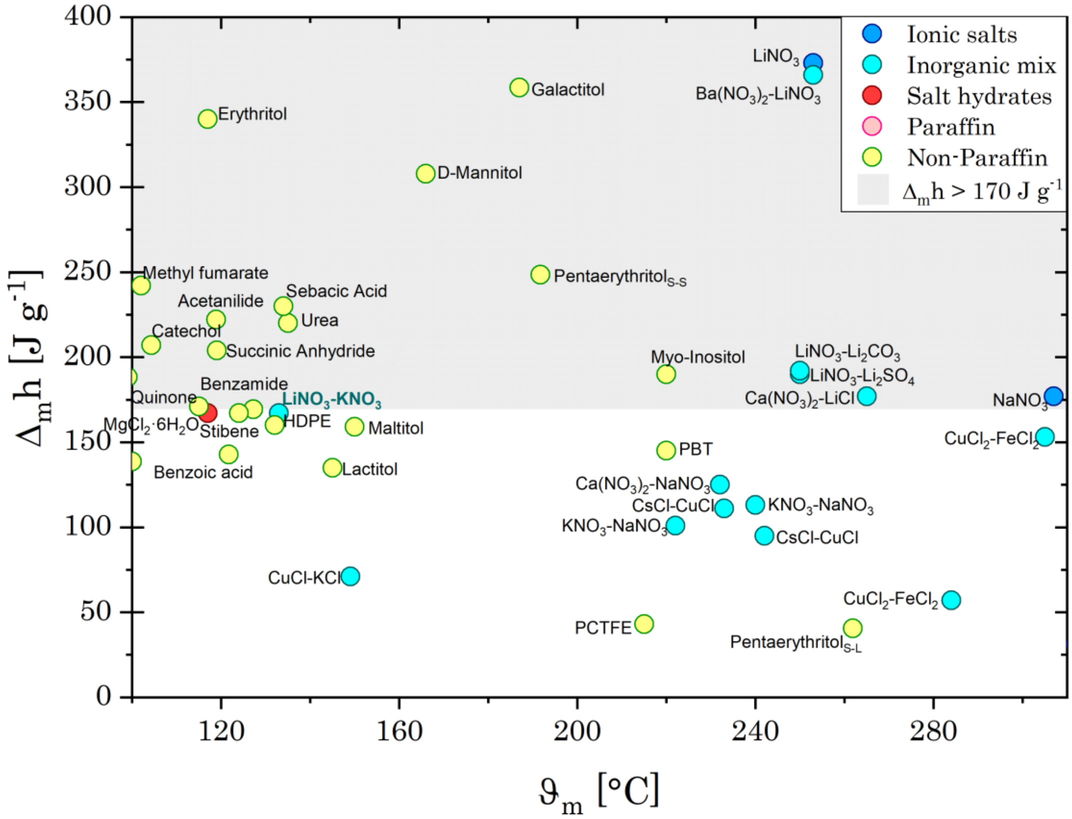

Figure 6: Plot of phase change materials characterized by the melting temperature ϑ_m and the phase change enthalpy $\Delta_m h$ (Source: DLR).

Furthermore, as was pointed out above for the HTHP and the ORC, the increase of the melting temperature of the PCM also influences the efficiencies of HTHP and ORC. While it means a higher heat sink temperature and thus lower COP for the HTHP, a higher melting temperature of the PCM means a higher heat source temperature and thus efficiency for the ORC.

<u>Active LH-TES storage concept:</u>

The current LH-TES is a passive PCM storage meaning that the storage capacity and the charging/discharging power are dependent on one another. Due to the limitations of the heat transfer between the refrigerant in the immersed HX and the PCM, the discharging power decreases more and more with increasing solidification of the PCM. Also, when charging the PCM storage, the thermal power that can be delivered to the PCM is not constant, but decreases with increasing charging process. This is a major drawback of such passive systems, since a constant charging and discharging power is preferred, not only for the HT-TESS, but also for having constant operating conditions for the HTHP and the ORC.

A solution for this is an active LH-TES storage concept in which the storage capacity and the charging/discharging power are decoupled from one another. This would realize a constant charging and discharging power. However, such active PCM storage concepts currently have a low TRL, at least for a storage of the size and application discussed here. For active latent heat storages using paraffins as PCM, there is the solution of microencapsulation [Dem 2015] or other supporting materials [Rah 2022], but paraffins are out of scope here due to their low melting temperature. From ice storages, a procedure using the mechanical or thermal removal of produced ice, which then falls into the storage vessel is known [Urb 2006] and such an approach could also be used for other PCM storages, at least for the solidification process. This has been researched at the lab scale and is in further development [Tom 2022]. Other active concepts that have been developed are a moving bed concept [Poin 2016] and a screw concept [Zipf 2013]. These concepts have so far only been tested at a lab scale and clearly, realizing such a concept for a LH-TES of a CHEST system will require quite some technological progress in active PCM storages.

General design of the LH-TES:

A general technological challenge in the construction of a large PCM storage is that, to date, there is little experience in such PCM storages, at several research institutions. From Concentrated Solar Power (CSP) plants, the use of solar salts in molten salt storage is well known. These are always kept liquid, i.e. they are not used as phase change materials. Larger scale PCM storages have been realized [Lai 2012] [Garc 2022], but none is operating in a real setting. The scale-up of the LHTES from a storage capacity of currently 160 kWh up to MWh scale requires technological development.

A decisive issue to mention here is the design of the heat exchanger, since heat transfer between a heat transfer fluid (HTF) and the PCM is always a key challenge in such storages due to the low thermal conductivity of the PCM. The (fin-tube) heat exchanger design must be adapted to the geometry of such MWh scale storages and optimized regarding the heat transfer, i.e. by number, diameter and length of the tubes, fin design or for instance also the use of heat transfer structures on the tube inner surface to increase the heat transfer coefficient. Since, as was said above, there is little experience with large PCM storages, perhaps, this HX design looks very different compared to what was developed for the CHESTER prototype. It could be a single-tube design if the HTHP and ORC use the same refrigerant, see Section 3.2.2. Furthermore, also the materials of the tubes and fins might be changed due to environmental impact and investment costs. Another aspect in the further development of the LH-TES is the reduction of heat losses through respective concepts for thermal insulation. Concepts for thermal insulation have been developed and would be applied in a relevant setting. In the prototype tested here, the thickness and type of insulation was a compromise between space and costs.

3.3.4. IE engine pump

The engine design developed and studied in the CHESTER project is one of the many possible versions of IE engines. It can be different depending on the application. Some ideas for the technological progress of this component are listed in the following:

- If the IE-machine is used only as a shaft power/electricity generator, the useful work can also be extracted directly from the driving piston by means of some kinematic (crank, swash plate, etc.) mechanism rather than by the hydraulic output.
- The reciprocating piston with the crank gear mechanism can be replaced with different rotary piston machines, which is more convenient in some cases. A straightforward example of such a machine is a so-called rotary lobe or Roots compressor/blower operating in a reverse mode, i.e., as a pressure-to-shaft-power converter.
- In case of high temperature operation, excluding conventional positive seals, a seal-less design can be used. The diaphragm-type IE engine-pump is an example of such an alternative design.
- Thermal efficiency can be increased by the use of a cascade, i.e. a combination of two or more IE-installations working at different temperature levels; each IE engine utilizes a certain temperature difference. The cascade also permits extension of the temperature difference covered by the simple non-regenerative cycles.
- The theoretical results obtained show a significant potential for improving engine performance through the use of mixtures of various working fluids. The mixtures could provide superior temperature matching in the regenerator between the working fluid at the high and low cycle pressures, offering much more effective heat regeneration. The use of mixtures could also be beneficial for superior temperature matching between the working fluid and the heat source and heat sink.
- Further improvements in thermal efficiency and power can be achieved by reducing friction and heat losses. Also, optimizing the engine intake and discharge valves as well as feed pump will help improve the engine performance.

4. Identification of required non-technological progress

4.1. Main objectives

Beside the technological progress that mainly aims at the reduction of CAPEX and the increase of efficiency of the CHEST system, see Section 3, also aspects of non-technological progress were identified. In principle, this can comprise a number of topics such as markets, taxation, legal regulation, etc., i.e. progress in CHEST´s environment that can help make this technology more viable, in particular from an economic point of view.

Since not all of these aspects can be treated in detail, only the most important ones will be discussed in the following. Furthermore, it must be clearly stated that the aspects discussed below will most likely not only mean progress for CHEST, but for electrical energy storage (EES) in general. Thus, also competitors of CHEST will benefit from these aspects, which could also turn out disadvantageous for CHEST in the end. There is quite a high uncertainty about the concrete effect that these aspects will have on CHEST.

4.2. Share of renewables in the energy system

The future development of the share of renewables, particularly for renewable electricity, is a very relevant factor for the progress of CHEST, mainly regarding the following two aspects:

- An increase of the share of fluctuating renewable electricity will require an increase of EES capacities. A massive switch towards renewables in the electricity generation will lead to amounts of electricity surplus that cannot be taken up by PHS and CAES technology due to their geographically limited capacities. Other technologies such as batteries or hydrogen storage (see Section 6) are there, but probably more expensive or limited by the scarcity of key materials (e.g. lithium).
- An increase of the share of fluctuating renewable electricity will also result in higher fluctuations of the electricity prices, since an economic incentive must be given to balance the high amounts of electricity surplus and deficit. These higher electricity price fluctuations will increase the revenues or savings that CHEST operation generates, respectively (see Section 4.3).

Since CHEST takes up both (renewable) heat and electricity, the increased share of renewable heat is in principle also advantageous for CHEST. This can be heat from various sources such as, waste heat, solar thermal or from biomass boilers or CHP plants. However, the increase of renewable heat is not an equally relevant progress in terms of CHEST´s boundary conditions like the increase of renewable electricity, since for heat storage as such, there are much simpler and cheaper solutions such as hot water storages. Furthermore, heat has a lower price than electricity, heat has normally a lower significance in the business model for CHEST and heat prices do normally not vary. As a consequence, the increase of renewable heat generation will have a considerably lower effect on the economic viability than the increase of renewable electricity generation, at least in general, i.e. on the level of a (national) energy system (locally, this might be different).

However, the increase of renewable heat will also lead to an increased need for sector coupling. In this context, CHEST is a suitable solution, since it combines the heat and the electricity sector through the uptake of heat and electricity from various renewable sources, the storage of electricity in the form of heat and the generation and supply of electricity and heat to the electric grid and e.g. a DH system or an industrial consumer. By offering a smart energy storage and management solution, CHEST will profit from the increase of both renewable heat and electricity in the energy system.

4.3. Electricity markets and electricity prices

The future development of the electricity markets and the electricity prices in general is a key aspect for the economic viability of CHEST, since CHEST is mainly an electrical energy storage (EES) and thus needs to generate profit with the uptake and supply of electricity. Even in applications where CHEST´s heat integration, i.e. the uptake of waste heat and/or the heat supply to a DH network or an industrial consumer, is an important aspect, electricity is required for the HTHP and generated by the ORC, which should give some economic profit.

Electricity markets:

The economic analyses in the CHESTER project showed that neither the participation in the spot electricity market alone (considering both historical prices and future projections for 2030 and 2040) nor a combination with the incomes from the tertiary regulation market (mFRR) would allow the annual incomes to overcome the annual expenses from running the system and repay the investment cost within the lifetime of CHEST components. Though, this combination also proved a right direction for improving the economy of the project as the net profit from the operation at both the spot and tertiary regulation market increased about 10 times compared to purchasing and selling the electricity only on the spot market. The key reasons for the CHEST system not giving its full potential at the current electricity markets includes:

- a relatively small amplitude of the fluctuations in the spot electricity market
- a relatively low number of very strong fluctuations
- a high taxation level for the consumed electricity by CHEST compared to the amplitude of the price fluctuations in the spot market [Del 23-b]

From a general point of view, an EES maximizes economic profit if there is frequent charging and discharging and the price to pay for the electricity uptake is low (or even negative, i.e. a revenue) and the revenue for generated electricity is high. This means that for a CHEST system participating in electricity markets, a high fluctuation of electricity prices is required. The analysis in the CHESTER project showed that the fluctuations in electricity markets such as the DAM are currently rather low and the regulation markets often do not show any market volume and/or there are low prices. With the increase of renewable electricity production, this situation should improve, since these RES show fluctuating electricity generation, which affects the electricity prices.The CHEST system fits in future electricity markets given the European power system will transform rapidly to integrate more renewables, develop flexibility and enable consumers to play a more central role. ENTSO-E has proposed the European balancing energy market target model. This will be especially crucial for new energy players such as demand response operators or aggregators and storage. The CHEST system is a suitable solution for this [Del 23-c].

Electricity prices aside from electricity markets:

In applications where CHEST does not directly participate in electricity markets, but e.g. operates as electrical (and thermal) energy storage for an industrial consumer, an industrial park or an energy community, there is often a constant electricity price – normally separated into a price for the maximum power supply and a price for the delivered electrical energy – as a result of a bilateral contract. In such a situation, CHEST can be useful to reduce the costs for the maximum power supply through electrical load shifting. However, this maximum power price is generally quite low and thus alone cannot provide economic viability for CHEST. In case of (renewable) electricity generators such as wind turbines or PV plants owned by the industrial consumer(s) or the energy community, CHEST can increase this renewable electricity generation and reduce the costs for the external purchase of electricity. However, this alone will mostly also not compensate for the high CAPEX of CHEST (or any other EES in general). A third element of economic profit for CHEST (and EES in general) would be the variation of prices for the delivered electrical energy, for instance, dependent on the daytime or other parameters. Thus, additionally to the two abovementioned possibilities, CHEST could generate savings by shifting electrical loads from times with high to times with low electricity prices [Star 2022].

As a conclusion, necessary progress in the boundary conditions for CHEST in such a situation would be:

- higher prices for the maximum power supply (price per kW_{el}), since this will increase CHEST´s benefit of peak load shaving.
- higher prices for the delivered electrical energy (price per kWh_{el}), since this will increase CHEST´s benefit of maximizing the electricity generation from the consumer´s own sources and minimizing external electricity purchase.
- variable electricity prices (price per kWh_{el}), since this will increase CHEST´s benefit of electrical load shifting.

While higher electricity prices are favorable for CHEST´s economic viability, but of course not in the consumer´s interest, variable electricity prices can be a win-win-situation for both the consumer and the electricity supplier, the DSO/TSO or others. With such a price scheme, the electricity supplier gives an incentive to save costs in times when its own costs are high so that in the end, both partners can reduce costs.

4.4. Regulations, fees and taxes

Fees, taxes and other surcharges on the heat and electricity price are a further relevant factor for the progress of CHEST, since they affect the economic performance of CHEST. In some countries such as Germany, the electricity price is dominated by these extra charges, e.g. electricity tax, transmission and concession fees and several surcharges (EEG, CHP), which results in a rather low percentage for the actual electricity production, distribution and profit margin.

The situation for CHEST in terms of taxation can be very different in the different EU countries and also very much depends on the specific application CHEST would be used for. For example, in Denmark, there is a tax on “regular” electricity and a considerably lower tax on electricity used to produce heat (power to heat). In Germany, there is one electricity tax, but since it has to be paid for the electricity that is consumed, it would apply only on the part of electricity taken up by CHEST that is converted to heat meaning that the P2P ratio of CHEST is essential in this context. For the transmission fees, the case would be similar and concerning the abovementioned surcharges, it depends for example on the type of CHEST integration (grid-connected or in “direct local connection” to e.g. a wind farm) and on the size of the system, among other factors.

These fees and taxes also depend on the interpretation of an energy storage as being rather an energy consumer, an energy producer, both consumer and producer or not completely defined what it is. In some cases, this can mean double taxation for CHEST or also an unclear situation on what would have to be paid for the electricity taken up and delivered by CHEST. Since all the different cases and respective tax and fee regulations cannot be treated here for the different EU countries, only some general conclusions on what would mean progress in the boundary conditions for CHEST are discussed in the following.

- First of all, a clear definition of the different types of energy storages in terms of taxation is required, i.e. whether they are treated as energy consumer or producer and that there is a clear regulation which fees and taxes have to be paid dependent on the application, storage size or whatever. This would facilitate the economic assessment of CHEST and other (electrical) energy storage technologies for different applications. Preferably, these definitions would be as simple as possible and similar across the EU countries.
- Second, double taxation for the heat and electricity consumed and delivered by CHEST should be avoided. This can partly be solved by the abovementioned clear definition of energy storages as either energy consumer or producer. With the increasing share of renewables in the energy system, it should be clear that increased capacities of energy storage are required. So, the relevance of such storages should be acknowledged by reducing financial burdens on energy storage. The revision of the Energy Taxation Directive (ETD) is a step to avoid double taxation by making it possible to consider energy storage facilities as redistributors [EASE 23-a].
- Furthermore, when it comes to concrete fees and taxes, the future development of CO_2 fees of any kind (emission trading system, additional fees) can have a positive effect on the further progress of CHEST. The further increase of such CO_2 fees one the one hand would result in an increase of the renewable energy generation, which is advantageous for CHEST, see Section 4.2. On the other hand, this would generally increase the value of energy storage as a means of energy efficiency measure.

4.5. Progress in modeling/simulation

Non-technological progress can not only be achieved by changing CHEST´s environment regarding markets, regulations, etc., as discussed above, but also by the better understanding of the technology through progress in respective simulation models. In particular, at a component level, the further development of models can then also be used to guide technological development.

As was explained in Section 2.2 quite comprehensively, many different models were already developed in the CHESTER project ranging from thermodynamic models of the main components (HTHP, ORC, LH-TES, SH-TESS, IE engine-pump) via CHEST system models of different level of detail up to models for the simulation of CHEST in a complete national energy system. This means, a solid basis for the theoretical analysis of CHEST components as well as the complete system was provided in the CHESTER project allowing to evaluate technical, energetic, environmental and economic performance of CHEST in a wide range of scenarios and boundary conditions. However, the following aspects for further progress, i.e. a better understanding of CHEST through theoretical analysis, were identified:

<u>Component models:</u>

In general, the developed component models gave satisfying results, i.e. that the experimental results were in good accordance with the simulations, see for instance Sections 2.2.1 for the HTHP and 2.2.2 for the ORC. One aspect that should be improved is the more realistic result for the efficiencies that were generally overestimated compared to the experimentally observed efficiencies, especially for the heat pump.

The modeling of the HT-TESS, as was explained in Section 2.2.3, involves several single models that can be coupled or used for analyzing specific issues. There is clearly need for further development of these models, e.g. concerning using suitable HTC correlations for the charging and discharging process and for different working fluids or the analysis of “secondary effects” on the heat transfer mechanisms. Furthermore, there is a need for modeling such active storage concepts that were proposed in Section 3.3.3.

Concerning the models for the IE engine-pumps, current research shows a significant potential for the technology. Therefore, theoretical studies towards better understanding of thermodynamic, thermal and fluid mechanical processes in the IE engines are of much interest and should be further developed.

<u>System models:</u>

In general, a sufficient number of CHEST system models with different focus and level of detail were developed, which is a good basis for a comprehensive analysis of the CHEST system.

One aspect of possible improvement could be the further development of the advanced TRNSYS model in terms of a more precise modeling of the CHEST system for different refrigerants and PCMs. Different combinations of these were tested in the CHESTER project, but what is so far neglected or considered only rudimentarily, is a change of more or less constructional details in the HTHP and ORC circuit when using different refrigerants and PCMs with different melting temperatures. For instance, depending on the type of refrigerant, in particular the shape of the saturated vapor line, i.e. retrograde (dry), anterograde (wet) or isentropic [Jock 2018] and depending on the temperature lifts, the number of compression stages and the design of the heat exchangers will vary. The more detailed consideration of this in such an advanced TRNSYS model would help to more precisely forecast the performance of the HTHP, ORC and the complete CHEST system for different refrigerants and PCMs. As was pointed out in Section 3.3.3, there is definitely a need to look for alternative PCMs. Thus, the extension of the model for other PCMs and the analysis of suitable PCM/refrigerant combinations would be a logical step of improvement concerning CHEST system modeling.

A further aspect of possible improvement is the consideration of ramp-up procedures in the advanced TRNSYS models or other CHEST system models, respectively. In the current models, this is neglected, which means that the HTHP and the ORC have a constant operation within a time step. However, in particular for the analysis of CHEST participating in regulation electricity markets, but also for the analysis of other applications, it would be useful to include the ramp-up behavior.

5. Identification of required R&D work

5.1. Introduction

Based on the current stage of the CHEST technology, with the conceptual, simulative and experimental results obtained and the challenges observed during the project, the required technological as well as non-technological progress was defined by the project partners, cf. Sections 3 and 4. In order to close these gaps and develop CHEST technology further towards the intended commercial applications described in Section 8 of this report, R&D activities have to be carried out. This chapter first of all gives a high-level perspective on the required R&D work for the development of CHEST technology. After this, detailed R&D activities that are derived from the identified technological and non-technological progress in Sections 3 and 4 are listed to give an overview on the multitude of R&D actions to be taken. Lastly, possible funding schemes and further programs and activities that are relevant for the outlined R&D work of CHEST are discussed.

5.2. Required high-level R&D activities

As was shown in the previous sections, the CHEST technology has been developed during the CHESTER research project up to a technology readiness level (TRL) of 5. This means, that a small-scale prototype with a charging and discharging power of 10 kW_{el} was built and tested in a laboratory environment under a variety of test conditions. This constructional and experimental work was accompanied by comprehensive theoretical work including techno-economic and environmental assessment as well as the analysis of different applications and business models.

Given the aforementioned current TRL of the CHEST technology and the required technological and non-technological progress identified by the partners (cf. Sections 3 and 4), the very next overall development step for the CHEST technology is the further increase of the TRL through respective research projects. On the one hand, this TRL increase refers to the individual main components of the CHEST system, such as the HTHP, the ORC and the HT-TESS, with their subcomponents such as the compressor, expander or the heat exchanger inside the latent heat storage. On the other hand, this TRL increase refers to the whole CHEST system and above all means a scale-up from currently 10 kW_{el} up to several 100 kW_{el} or later beyond 1 MW_{el} in a demonstration project.

Concerning the main components and subcomponents, the development details are given in the next sections. From an overall perspective, the main focus lies on the increase of performance through increase of efficiencies and the decrease of investment costs. A further objective is the increase of temperatures, i.e. the increase of possible HTHP heat sink and ORC heat source temperatures, which opens the door for further PCMs to be used in the latent heat storage. Furthermore, a scale-up of HTHP, ORC and HT-TESS technology has to be made, which goes along the abovementioned scale-up of the overall CHEST system. For the HT-TESS, the main challenge is that there is to date no experience on really large latent heat storages that would be required for large-scale CHEST systems. For the HTHP and ORC, a scale-up can be realized by using known turbomachinery technology, but the challenge here is to adapt it to the specific needs of CHEST and ensure proper interaction of the components.

The build and operation of a large-scale demonstration system is the necessary next step from system perspective to increase TRL of CHEST technology up to 7. Beside the already mentioned scale-up of the whole system, the main objective here is to analyze the operation of the CHEST system in an intended environment. In contrast to the tests performed for the small-scale prototype in the laboratory, this will generate experience with CHEST that is integrated into an energy system under the boundary conditions of a concrete demo site and for a specific application. Such a demonstration project, although still at pre-commercial scale, will also advance manufacturing aspects, cost reduction and concretize the feasibility of a specific business case.

As a longer-term high-level R&D task, i.e. for the next decade(s), several demonstration projects lifting CHEST´s TRL beyond 7 need to be carried out in order to:

- optimize component and system operation to achieve maximum efficiencies
- reduce CAPEX considerably
- collect knowledge and practical experience on the operation of real-size CHEST systems under various boundary conditions and in different applications
- realize changes in the system construction and selection of materials to reduce the environmental footprint of the CHEST system
- evaluate economic viability from the use of CHEST for several applications and respective business cases

These demonstration projects will finally bring CHEST technology to a commercial status (TRL 9) and will clearly show the applications where large-scale CHEST systems are an economically viable storage solution.

5.3. Detailed R&D activities

5.3.1. R&D activities for CHEST components

Based on the current stage of the CHEST technology, the results and challenges observed during the project and the identified required technological and non-technological progress, detailed R&D activities were derived that are listed in the following tables.

Table 1 shows the required R&D activities for the HTHP and the ORC. As was pointed out in Section 3, the main objectives here are the increase of the efficiencies, the development of HTHPs and ORC for higher temperatures and the combined use of HTHP and ORC components.

Table 2 shows the required R&D activities for the HT-TESS. As was pointed out in Section 3, the main objectives here are the use of alternative PCMs and the development of suitable storage designs for MWh-scale.

Table 3 lists some selected R&D activities for the IE engine-pump. This technology generally requires further research and scale-up of power, not only for the use in a CHEST system.

Table 1: Overview on required R&D activities for the HTHP and the ORC.

Project results and required progress	Derived R&D activities
- Different refrigerants are used in the HTHP and ORC cycles and at least partly, they still have a certain environmental impact → Refrigerants that are suitable for both HTHP and ORC must be found, to allow combined HTHP component and a single-tube HX design in the LH-TES → Refrigerants must be environmentally friendly, i.e. with an ODP of zero and a GWP of nearly zero	- Screening of suitable refrigerants through systematic literature review - Theoretical and/or experimental characterization of properties in case of missing information on these properties - Analysis of the performance of these refrigerants in the HTHP and ORC cycle with the help of dedicated simulation studies, if necessary incl. the further development of the respective simulation models
- Knowledge on suitable lubricants and their interaction with these alternative refrigerants is missing → Suitable lubricants for these refrigerants and the designated higher temperatures must be identified	- Screening of suitable lubricants through systematic literature review - Theoretical and/or experimental characterization of properties in case of missing information on these properties - Laboratory tests on the refrigerant / lubricant interaction
- HTHP heat sink temperatures are currently limited to about 150 - 180 °C → Compressors and heat pumps for higher heat sink temperatures (200 °C and beyond) must be developed, respectively → Turbomachinery technology must be used to achieve higher temperature levels and higher efficiencies	- Development of new or adaption of existing compressors for higher heat sink temperatures through theoretical, constructional and experimental analysis - Adaption of existing turbomachinery to the specific needs of a HTHP and an ORC in a CHEST system - Elaboration and experimental testing of measures to increase the efficiency of HTHP and ORC
- Separate HTHP and ORC component mean a certain CAPEX → HTHP and ORC are supposed to form one component or at least partly use several component parts together	- Conceptual analysis of constructional designs for a combined HTHP/ORC component - Development or adaption of existing turbomachinery compressors and expanders to be used for both purposes under CHEST operating conditions
- Current ramp-up times of 5 min for the HTHP and 15 min for the ORC are too high for certain applications → HTHPs and ORCs with lower ramp-up times must be developed	- Analysis of limiting factors determining the ramp-up time (in turbomachinery) - Elaboration of measures, constructional and concerning control, to decrease ramp-up time

Table 2: Overview on required R&D activities for the HT-TESS.

Project results and required progress	Derived R&D activities
- PCM shows low environmental performance and is relatively costly → PCMs with appropriate properties (melting temperature, chemical stability, environmental footprint, etc.) must be found	- Theoretical and/or experimental characterization of thermal and other properties such as: melting temperature, phase change enthalpy, thermal conductivity, density, cycle stability, corrosion interaction, price - Analysis of the CHEST system performance for different refrigerant/PCM combinations through dedicated system simulations
- Heat exchanger inside the PCM storage needs relatively much material and therefore has significant contributions to CAPEX and environmental footprint → Heat exchanger designs must be optimized in terms of heat transfer and the material use → Heat exchanger designs for large-scale PCM storages must be elaborated	- Optimization of material use for specific heat transfer rates, e.g. by CFD simulations, on the heat exchanger designs - Experimental testing of large-scale PCM storages in demo projects (see also below)
- Little experience with large-scale PCM storages (storage capacities of MWh) - Low TRL (up to 4) of active PCM storage concepts → PCM storage design needs to be improved and upscaled → Active PCM storage concepts need to be lifted to higher TRL	- Detailed theoretical analysis of the performance of active concepts - Upscaling and improvement of selected active PCM storage concepts - Further elaboration of large-scale storage designs and controls (both active and passive concepts) - Experimental testing of large-scale PCM storages in demo projects

Table 3: Overview on required R&D activities for the IE engine-pump.

Project results and required progress	Derived R&D activities
- IE engine pump technology is still at a relatively low TRL - Power output is still relatively low (< 1 kW) → Major advancements for the different types (e.g. Bush and Worthington type) required → Technology must be scaled up to kW range → Efficiency must be further improved	- Detailed thermodynamic analysis of the various types/variants, for instance regarding thermal losses or the use of suitable refrigerant mixtures - Elaboration of scale-up possibilities, for instance through cascades - Experimental tests in laboratory environment - Experimental tests in applications outside the lab, with different purposes/services of the IE engine-pump (shaft power, electricity, pumping liquids)
- Development of IE engine-pump was decoupled from build of CHEST prototype in the CHESTER project → Integration of an IE engine-pump into a CHEST system must be realized	- Elaboration of concrete integration possibilities of an IE engine-pump into a CHEST system, e.g. as an ORC pump - Lab tests with pumps driven by an IE engine

5.3.2. Further R&D activities for CHEST

Beside the mostly technologically oriented R&D activities for the CHEST main components, further (theoretical) analysis and R&D work related to the (operation of the) entire CHEST system is required and could accompany the abovementioned activities. Table 4 gives an overview on these further R&D activities.

Table 4: Overview on further required R&D activities.

Project results and required progress	Derived R&D activities
- Component and system models are there, but some potential improvements were identified → Component and system models might be extended/optimized and adapted to the planned system improvements	- Implementation of further features or more detailed calculations in the existing component and system models - Adaption of the models to the new design of HTHP/ORC and HT-TESS and the new materials (e.g. PCM)
- LCA was conducted only for a CHEST system with the materials and configuration of the CHESTER prototype → Environmental performance evaluation needs to be adapted to new materials (PCMs, etc.) and system designs	- Execution of LCAs for large-scale CHEST systems using other e.g. PCMs and with other system designs - Comparison of different materials and system designs from environmental point of view - If relevant: execution of LCAs for production processes of key materials/parts of CHEST components in order to derive environmental footprint mitigation measures

- Smart Energy Management System (SEMS) so far does not give optimum results - SEMS has not been tested in a real environment yet → SEMS must be improved and adapted to further possible applications	- Analysis of suitable algorithms for the forecast of electricity prices - Further development of the SEMS optimization module concerning a more sophisticated logic and suitability for different applications - Development of an interface to couple SEMS with a real CHEST system
- Only limited analysis of legal situation, regulations, (electricity) markets, fees and taxes possible in the CHESTER project → Analysis should be more comprehensive and extended to more EU countries	- Systematic analysis on legal situation for electrical energy storage, regulations, electricity markets, fees and taxes that are relevant for CHEST (with regular revisions to follow the permanent changes) in the most important EU countries - Determination of (the most) suitable conditions and use cases to realize demo projects and later on commercial ones - Detailed elaboration of recommendations for policy makers
- Analyzed business cases mostly showed a poor economic performance for CHEST → Economic performance analysis should be updated with the further technological advancement → Further business cases should be identified	- Update of economic assessment for new system design and materials, incl. the analysis on markets, fees, etc. - Elaboration of new business cases that might arise from changes in the boundary conditions (markets, regulations, taxes, etc.)

5.4. Proposed R&D funding schemes and further activities

On the one hand, the R&D activities mentioned in Section 5.3 can be realized via national funding opportunities in the different EU countries. On the other hand, and this is seen as the most important funding scheme here, this can be done in the framework of the current EU funding program Horizon Europe. In particular, two relevant calls of this program were identified:

- HORIZON-CL5-2023-D3-01-13: Development of novel long-term electricity storage technologies
- HORIZON-CL5-2023-D3-01-14: Demonstration of innovative, large-scale seasonal heat and/or cooling storage technologies for decarbonisation and security of supply

Especially the second call is interesting for a demonstration project lifting CHEST technology to TRL 7 as was discussed in Section 5.2. There are also other calls like HORIZON-CL5-2023-D3-02-04 (Innovative components and configurations for heat pumps) that can be used for funding R&D activities for a certain component of CHEST, in this case the heat pump. More details about funding opportunities are discussed in a report on the exploitation activities for CHEST [Del 23-a].

R&D progress for CHEST can also achieved via the collaboration with other similar research projects and initiatives. One interesting example to mention here is the IEA Energy Storage Task 36 on Carnot batteries [IEA EST36] or its follow-up task on zero-carbon (industrial) heat and power supply (preliminary working title), respectively. Since CHEST is a certain type of a "Carnot battery", i.e. a power-to-heat-to-power storage, further development in this field can also be relevant for CHEST.

In the IEA Energy Storage Task 36, which is currently about to finish, some of the partners of the CHESTER consortium were already actively or passively involved. Beside the work on the categorization and characterization of the different types of Carnot batteries, two subtasks are of special interest also for CHEST:

- a subtask on definitions in which key performance indicators (KPIs) at the material, component and system level were defined and the language in this field of Carnot batteries was standardized,
- a subtask on the analysis of markets, energy systems, policies and regulations in which for instance market requirements were identified and recommendations for policy makers as well as other dissemination measures were elaborated.

Due to the abovementioned involvement of some of the CHESTER partners, results elaborated in the IEA Energy Storage Task 36 were brought into the CHESTER project, and vice versa, results from the CHESTER project were also useful input to this Task.

The follow-up task that is currently in the task definition phase aims at looking at Carnot batteries in its full complexity, i.e. to analyze in detail in which applications and under which boundary conditions the various power-to-heat(-to-power) options are energetically, environmentally and economically reasonable. This means that not only the power output of Carnot batteries is in the focus of this work, but also the heat output – either as high-temperature heat directly taken from the Carnot battery´s TES and used for industrial processes or as low-temperature heat generated in the power cycle and used for heating purposes in e.g. a DH system. Through these analyses, the share of renewables in the heating sector (by integrating renewable electricity but also renewable heat) shall be increased and the decarbonization of the heating sector shall be advanced.

As a general objective, both for the existing Task 36 and the follow-up task, a platform that brings together experts from academia and industry shall be established and perpetuated, in order to analyze the future perspectives of power-to-heat(-to-power) systems and strengthen the international visibility of these options in industry and policy.

There are also further tasks in the IEA Energy Storage Technology Collaboration Programme that might be interesting for the further development of CHEST and thus could be an option to have an exchange with or being actively involved in:

- Task 35 on flexible sector coupling (about to finish) [IEA EST35] that deals with different storage technologies for the coupling of sectors, in particular by taking up renewable electricity from wind and PV to transfer this electricity to mainly the heating/cooling sector, but also the mobility sector. Since CHEST is a flexible storage system that couples the electricity and heat sector, this concept can be fed into this task as an innovative alternative. On the other hand, it would be useful to look at the sector coupling solutions and storage concepts considered in Task 35 in order to evaluate possible competitors for CHEST in this point of view.
- Task 37 on smart design and control of energy storage (currently running) [IEA EST37] that deals with the optimization of control strategies for energy storages taking into account both supply and demand side and using for instance artificial intelligence. The exchange with this task could especially be interesting for the further development of the smart energy management system (SEMS). One particular aspect to mention here is the development of prediction methods, for instance for renewable energy production and for electricity prices, which is very relevant for SEMS.
- Task 39 on large thermal energy storages for district heating (currently running) [IEA EST39] that deals with the development of different technologies for large-scale low-temperature thermal energy storages (LTES) used in DH systems such as pit thermal energy storage. This can be interesting for CHEST development since an LTTES is an optional component to be coupled with a CHEST system.

6. Technologies competing with CHEST

6.1. Introduction

As CHEST is an energy storage system that offers both electricity and heat services, there are in principle many types of storage and storage systems that could be competitors to CHEST, see Section 6.2. The main objective here was to elaborate on the most relevant competitors and link them to the applications and business cases where they compete with CHEST, see Sections 6.4.

After a screening of relevant technologies, more information on the most relevant competitors was collected, especially concerning the following points:

- stage of development: technological maturity and challenges, (roundtrip) efficiencies, costs, see Section 6.3
- potential and expected development in the next decade(s): technological development leading to e.g. cost reduction and efficiency improvement, but also perhaps extension of possible applications, less environmental impact, etc., see Section 6.5

This analysis was carried out in order to achieve the following conclusions (Section 6.6):

- identification of advantages and disadvantages of CHEST compared to its competitors, per application / business case
- evaluation of the most appropriate storage solution for a certain application and conclusion, whether CHEST is a reasonable option for a certain application
- final conclusion on which applications and business cases CHEST should focus on, see also Section 8

6.2. Overview on technologies competing with CHEST

6.2.1. Pumped hydro storage (PHS)

Pumped hydro storage is currently the main type of grid-scale electricity storage. In the charging process, electricity is used to pump water from a reservoir of lower elevation to a reservoir of higher elevation. In the discharging process, the stored gravitational potential energy is converted back into electricity when the water flows back to the reservoir of lower elevation and thereby drives a water turbine that drives an electric generator [Ste 2020]. Pumped hydro storage can offer several grid electricity services and is therefore an important competitor for CHEST.

6.2.2. Hydrogen storage (fuel cell)

In the context of this report, mainly power-to-hydrogen-to-power systems are considered as competitor for CHEST. Hydrogen is produced in an electrolyzer with the help of (renewable) electricity and then stored in a pressurized tank. The hydrogen is later used in a fuel cell to generate electricity and heat. On the other hand, the conversion of surplus renewable electricity to hydrogen in order to use this hydrogen as a “green fuel” e.g. for the decarbonization of high-temperature industrial applications also poses a competitor for CHEST, but only concerning the uptake of electricity.

6.2.3. Chemical energy storage

Like for a hydrogen storage system, surplus electricity can be converted to other e-fuels (PtX). These can be either gases (PtG) such as methane / natural gas, or liquids (PtL) such as methanol and kerosene. This normally includes the production of hydrogen in an electrolysis plant, the use of CO_2 coming from the ambient air or an industrial or biogas plant and further processing steps to produce the fuel [Hank 2018]. These e-fuels can be stored and transported via pipeline or vehicles and then converted back into energy. In case of methane, electricity and/or heat can be generated. Methanol can either be used in a fuel cell or, as oxymethylene ether, replace diesel and gasoline fuels in cars [Hank 2018-2]. Thus, application for methanol will mostly be mobility, which is also true for kerosene. This application in vehicles is not considered here as a competitor to CHEST, but like for hydrogen storage (see above) only those applications where e-fuels are converted back to electricity and/or heat.

6.2.4. Batteries

In batteries, energy is stored in electrochemical form, which gives possibility for a multitude of different battery types. Only those types that are currently most important or show high potential in the future will be treated in the competitor analysis in Section 6.3 and the following sections. Again, mobile applications are out of scope of this report, since they do not directly represent a competitor to CHEST.

6.2.5. Compressed air energy storage (CAES)

Surplus electricity can be used to compress air and store it in underground cavern (CAES charging cycle) in order to later generate electricity by using the compressed air to drive a gas turbine (CAES discharging cycle). While the compression process requires cooling, heat must be supplied to the air before expansion in the turbine, which is mostly done by the combustion of natural gas. In the so-called advanced adiabatic CAES concept (A-CAES or AA-CAES), thermal energy storage is used to store the heat of the air compression and heat up the air before expansion, thus avoiding the combustion of fossil fuels [Luo 2014].

6.2.6. Liquid air energy storage (LAES)

The liquefaction of air requires electricity for a compressor while liquid air can be used in a power cycle to generate electricity in a turbine. Thus, this can form the charging and discharging cycle of an energy storage system transforming electricity to liquid air and back to electricity. LAES can be used in grid-scale electricity storage where it is a competitor to CHEST [OCal 2021].

6.2.7. Carnot batteries

As indicated by the basic schematic in Figure 7, a Carnot battery is an energy storage system that converts electricity to heat, stores this heat at a high-temperature level and converts it back to electricity. The transformation A from electricity to high-temperature heat can be realized by a resistive heater or by any type of heat pump using for instance a Brayton or a Rankine cycle. In case of a heat pump, low-temperature heat is also needed as an input to the storage system. The high-temperature heat can be stored by any kind of thermal energy storage: sensible, latent or thermochemical. The transformation C back to electricity is done by a power cycle, e.g. Brayton or Rankine cycle, and beside electricity also gives low-temperature heat as an output [IEA EST36].

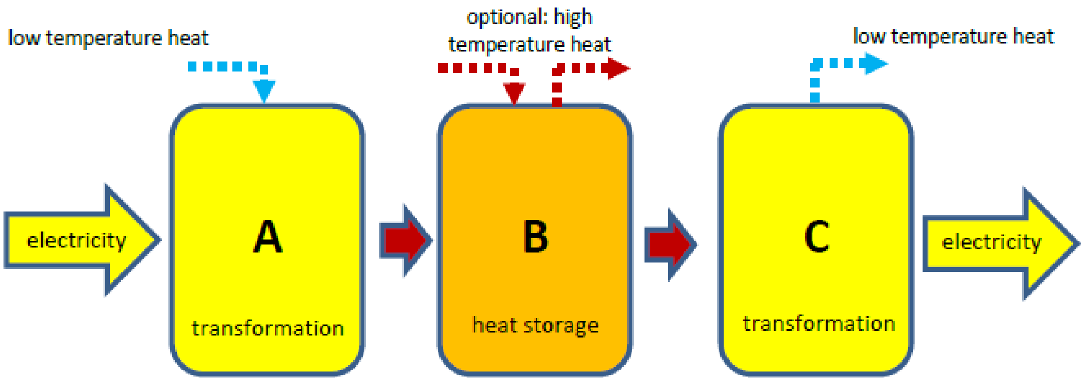

Figure 7: Schematic of a Carnot battery [IEA EST36].

The CHEST system is a certain type of Carnot battery using sub-critical Rankine cycles for both transformation A from electricity to heat and C from heat to electricity and a combination of latent and sensible thermal energy storage. Given the description above, there are a lot of possibilities to form a Carnot battery by the different technologies for the steps A to C and also concerning the temperature levels for heat sources and sinks. Many of these other types of Carnot batteries can be competitors for the CHEST system.

6.2.8. Flywheel energy storage (FES)

Flywheels are used for short-term electricity storage in which storage happens in the form of rotational energy. Mobile applications in vehicles are not considered here, but only (larger) stationary flywheel energy storage systems that could be a potential competitor for CHEST.

6.2.9. Supercapacitors

Supercapacitors are an advanced type of capacitors mostly used in mobile applications (not considered here) for short-term storage of electricity. In the context of this report, only (larger) stationary supercapacitors are treated as potential competitors for CHEST.

6.2.10.Superconducting magnetic energy storage (SMES)

With this type of storage, electricity is stored in a magnetic field induced by a coil made of superconducting material. This enables an electricity storage almost free of losses. However, extensive cooling is required to keep the coil at temperatures where the material shows its superconducting property.

6.2.11.Thermal energy storage (TES)

As mentioned above, also thermal energy storage technologies have to be considered as potential competitors for CHEST, since a CHEST system not only generates electricity, but also heat. CHEST offers the possibility to shift its output towards electric or thermal output depending on the boundary conditions (electric and thermal demand, heat source and sink temperatures). So, there might be times when CHEST rather operates as a thermal storage and as such has a variety of competitors, e.g. sensible, latent and thermochemical TES with a plenty of different storage media.

6.3. Current stage of development

In the following, some basic information about the most relevant competing technologies are provided in order to show their main properties. The most important properties for the selection of one or another technology for a certain application are:

- charging and discharging power
- storage capacity
- response time
- charging and discharging time, which is basically given by the storage capacity and the charging and discharging power
- efficiencies: efficiency of charging, discharging and storage process, roundtrip efficiency
- costs: CAPEX, OPEX, levelized costs of storage (LCOS)
- energy density given by the storage capacity and size

Further properties to consider are for instance:

- geographical constraints
- lifetime
- technological maturity
- safety and environmental concerns

Figure 8 shows a comparison of the most important energy storage technologies regarding the charging/discharging power (power rating) and the storage capacity (rated energy capacity) as well as the discharging time as given by Luo et al. [Luo 2015]. Furthermore, the range that is supposed to be relevant for CHEST is highlighted by a red dashed circle.

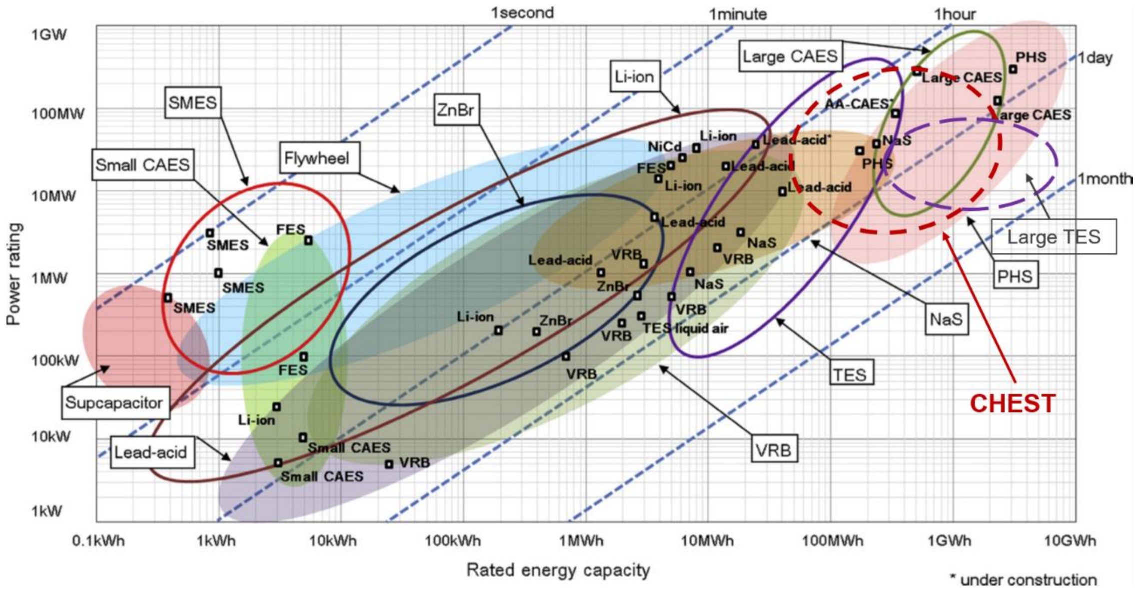

Figure 8: Comparison of charging/discharging power (power rating) and storage capacity (rated energy capacity) with discharge time duration at power rating for different energy storage technologies according to Luo et al. [Luo 2015], extended with CHEST and large TES technology.

CHEST is supposed to be a storage technology basically starting at a power of about 1 MW_{el} and with typical sizes of several tens of MW_{el}. In principle, also larger powers of > 100 MW_{el} should be possible from a technological point of view, but this may not be the most favorable size. The storage capacity and the charging/discharging power of a CHEST system will be chosen in a way that the discharging time will typically be in the order of magnitude of several hours.

This figure gives a first impression on which technologies will be competitors to CHEST and which rather will not. For instance, supercapacitors, flywheel energy storage and superconducting magnetic energy storage are much smaller compared to CHEST in terms of power and/or storage capacity. Batteries cover a wide range of power and storage capacity and at least partly overlap with the range CHEST will be active in. The most relevant competitors in terms of power and storage capacity, as can be seen from the figure, will probably be PHS and large CAES. Furthermore, thermal energy storage (TES) and in particular large TES cover parts of the range CHEST is active in and therefore can also be a competitor. Hydrogen storage is not mentioned in the figure, but can cover a wide range of storage capacities and power from small-size systems up to rather seasonal use. Thus, in principle, it will at least partly be a competitor to CHEST.

Table 5 shows the comparison of CHEST with selected electrical energy storage (EES) technologies concerning further properties. The values specified for CHEST are thought to be achievable for a future CHEST system based on the results of the CHESTER project. The values for the other EES technologies were retrieved from Schmidt et al. [Schm 2019], Luo et al. [Luo 2015] and [EASE 23-b], and are considered to be typical numbers for these technologies. As can be seen from the table, these numbers sometimes show enormous ranges. Nevertheless, this provides a basic picture of these technologies.

Table 5: Comparison of CHEST with other selected EES technologies [Schm 2019] [Luo 2015] [EASE 23-b].

Technology	Roundtrip efficiency [%]	Response time	CAPEX [€/kW]	CAPEX [€/kWh]	Lifetime (shelf life) [a]
PHS	70…85	sec - min	400…3,800	10…150	40…60
Hydrogen storage	20…50	seconds	1,500-5,000	15…30	15…20
Lead-acid batteries	65…85	(milli)seconds	100…650	100…400	10
Li-ion batteries	75…90	(milli)seconds	150…1,300	600…2,500	15
CAES (diabatic)	40…55	sec - min	400…1,200	10…150	20…40
LAES	55…80	≥ 5 min	500…3,500	60…600	25…35
Flywheels	90	< 1 s	250…600	1,000…5,000	15…20
Supercapacitors	90…95	< 1 s	100…450	300…13,000	15
SMES	95…98	< 1 s	200…470	1,000…>10,000	20…30
CHEST	30…85	5…15 min	> 3,000	25…100	30

Despite the sometimes quite enormous ranges, several clear conclusions can be drawn from Table 5 and Figure 8:

- First of all, there are EES technologies such as flywheels, supercapacitors and superconducting magnetic energy storage (SMES) that have very fast response times in the milliseconds range and a very high roundtrip efficiency of typically well over 90%. They are characterized by rather small storage capacities, but high capacity-specific investment costs of several thousand €/kWh. Furthermore, they have small to medium power and rather low power-specific investment costs. The main purpose of these technologies is to quickly deliver a certain (regulation) power, but for a rather short time of seconds to minutes; that is why they do not need high storage capacities.
- On the contrary, there are technologies such as pumped hydro storage (PHS) and compressed air energy storage (CAES) that have high storage capacities, high charging/discharging powers and react relatively slowly. Their roundtrip efficiency is medium (CAES) to high (PHS) as well as their lifetime, and their capacity-specific investment costs are very low.
- Thirdly, there are a number of battery technologies that cover a wide range of storage capacity and power. Their roundtrip-efficiencies are relatively high up to 90%, but on the other hand, they have rather low lifetimes.
- Lastly, there are some other technologies that do not fit into the aforementioned groups such as hydrogen storage and liquid air energy storage. In principle, they can be used in different applications, but will face several competitors with that.

CHEST, as was stated above, is supposed to have a rather high storage capacity of several 100 MWh and power of several 10 MW_{el}, respectively. Given its low response time of currently about 5 min for the charging via HTHP and 15 min for the discharging via the ORC, it fits best into the second category with PHS and CAES.

Concerning the currently installed storage power and capacity installed worldwide, PHS is by far the most important storage technology. Figure 9 shows the globally installed storage power for different storage technologies in the year 2017. About 96% of the totally installed storage capacity of 176 GW_{el} is covered by PHS. Thermal energy storage accounts for about 3.3 GW_{el} or 1.9% of the totally installed capacity with molten salt thermal storages (predominantly used in CSP plants) being the most important one. Electro-chemical storage is based on several technologies with Li-ion batteries currently making up the highest share. In the field of electromechanical storage, CAES and flywheels are the two available storage technologies that together account for about 1.6 GW_{el} or 0.9% of the total installed power. For both CAES and flywheel technology, there are in principle only two to three large projects worldwide that dominate their deployment [IRENA 2017].

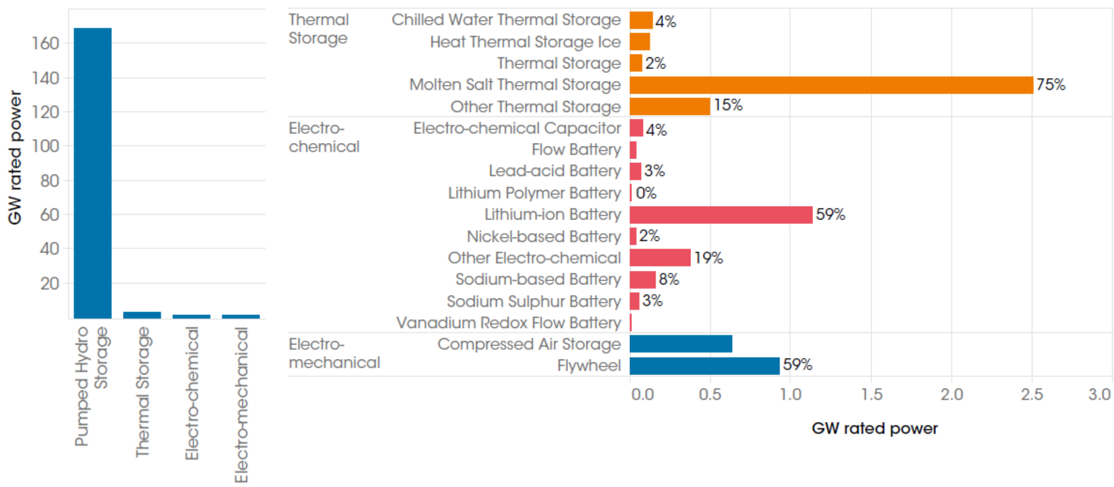

Figure 9: Global operational electricity storage power capacity by technology, mid-2017 [IRENA 2017].

In Europe, there is an installed storage power of about 60 GW_{el} and also here, PHS is the dominating technology concerning the installed power and capacity [EASE 2021]. It is interesting to note that more than 80% of Europe´s installed PHS capacity was commissioned between 1960 and 1990 under regulated market structures with regional or national monopolies while only about 5% was realized under liberalized market conditions [Bar 2016].

6.4. Competitors per application

The properties mentioned above, especially the power, the storage capacity and the response time, define the respective technology´s suitability for a certain application. Table 6 gives an overview of the suitability of selected EES technologies incl. CHEST for certain EES applications.

Table 6: Suitability of selected EES technologies for certain EES applications [Schm 2019].

Application	PHS	Hydrogen storage	CAES	Lead-acid batte-ries	Li-ion batte-ries	FES	Super-capaci-tors	CHEST
Energy arbitrage	✓	✓	✓	✓	✓	-	-	✓
Primary response	-	✓	-	✓	✓	✓	✓	-
Secondary response	✓	✓	✓	✓	✓	✓	✓	?
Tertiary response	✓	✓	✓	✓	✓	-	-	✓
Black start	✓	✓	✓	✓	✓	✓	✓	?
Seasonal storage	✓	✓	✓	-	-	-	-	✓
T&D investment deferral	✓	✓	✓	✓	✓	-	-	✓
Congestion manage-ment	✓	✓	✓	✓	✓	-	-	✓
Bill ma-nagement	-	✓	-	✓	✓	-	-	✓
Power reliability	-	✓	-	✓	✓	-	-	-

First of all, this table shows that hydrogen storage as well as the several types of batteries are in principle suitable for nearly all applications in the field of electricity storage. As a consequence, to compete with these technologies, argumentation will mainly have to be on properties such as costs, lifetime or further issues (e.g. environmental).

Secondly, technologies such as flywheels and supercapacitors, due to their fast response times and low capacities, are mainly used for fast corrections of imbalances in the electricity grid in order to stabilize the grid´s frequency. As can be seen from this table, these are applications that CHEST cannot deliver, since the response time of CHEST is too high to do so.

Furthermore, the table clearly shows that for every EES application CHEST is supposed to be suitable for, there are already several competitors in place. For instance, energy arbitrage service can be realized by PHS, CAES, hydrogen storage and the various types of batteries. The same is true for tertiary response, T&D investment deferral and congestion management. When it comes to a seasonal storage of electricity, only technologies with high capacities such as PHS, CAES and hydrogen storage are relevant, but this is not a suitable application for batteries. However, batteries are an important competitor to CHEST in terms of services for bill management, i.e. to purchase power in times of low electricity prices and supply power by the storage in times of high electricity prices, which means savings in electricity costs for instance for an industrial consumer. Secondary response is a service that is currently not thought to be an option for CHEST because of the too high response time, but could be an option in the future when in particular the response time of the ORC can successfully be reduced. Black start should in principle be possible for CHEST to provide, but was not further analyzed here. Anyway, as can be seen from the table, CHEST would compete with several other technologies with the two services of secondary response and black start.

In terms of the ability of CHEST to take up, store and deliver heat, in principle all kinds of heat storage, i.e. sensible, latent and thermochemical TES with a plenty of different storage media are competitors to CHEST. Selection of the type and storage media will mainly depend on the temperature levels of the heat source (e.g. waste heat, RES) and the heat sink (e.g. DH system). Compared to a pure thermal energy storage, CHEST will always show higher costs and also lower efficiency (related to thermal output). However, it does not make sense to compare CHEST and only TES directly against each other, since CHEST would never be installed to only act as thermal energy storage. CHEST will always somehow be used as an electricity storage and in most cases, electricity storage will also be the more relevant aspect, at least from economic point of view.

6.5. Future development

As was shown above, pumped hydro is currently by far the dominating EES technology worldwide and in the EU. However, this will likely change and especially batteries will show massive deployment in the coming years, with an expected 17-fold increase in stationary applications by 2030. This is mainly due to the fact that battery costs are expected to decrease significantly, by about 50% to more than 60% in the year 2030. Furthermore, since battery storage is based on multiple technology options, there is still huge potential for further improvement of performance and new cost-effective solutions. In contrast to that, PHS is a mature technology with decades of operating experience. No improvements in terms of performance and costs are expected in the coming years [IRENA 2017].

Looking at the predicted development of levelized costs of storage (LCOS), this will change the share of installed capacities in several applications/services from PHS to batteries such as for the supply of secondary and tertiary response, but also for black start, congestion management and energy arbitrage. For seasonal storage, hydrogen storage will become the most relevant storage technology in terms of minimum LCOS [Schm 2019].

The potential for the realization of further PHS capacities is very limited due to the limited availability of suitable sites as well as stricter environmental standards. There are indeed some innovative approaches to make further PHS potential accessible, for instance by using abandoned mines or the sea as reservoir. However, this is also challenging and will very probably lead to higher investment and/or operational costs [IRENA 2017]. In Europe, the potential for further PHS accounts for about 15 GW by 2030 and 30 GW by 2050 according to a study on energy storage by the European commission [ECA 2020]. This means, the total installed power of PHS in Europe would be about 80 - 90 GW in 2050. According to another estimate based on IEA scenarios, PHS capacity in Europe will increase from currently 57 GW to 91 GW (lowest estimate) or even 188 GW (highest estimate) in 2050 [EASE 23-b].

The future potential for compressed air energy storage (CAES) must also be evaluated as quite limited. In terms of efficiency, the use of a thermal storage to store heat from the charging stage in order to use it in the discharging stage (advanced adiabatic compressed air energy storage, AA-CAES), increases the roundtrip efficiency up to about > 70% [EASE 23-b], but also investment costs. However, this is not mature technology, but in the process of demonstration [EASE 23-b]. In general, it must be stated that up to now, only very few CAES plants have been realized being rather demonstration than commercial projects. Furthermore, costs very much depend on the fact whether there is a suitable cavern available or has to be excavated right for this purpose. Due to that, the limited availability of suitable sites in conjunction with high costs is thought to be the main factor limiting the further increase of CAES capacities [IRENA 2017].

Beside the development of these existing technologies, there is the relatively young technology of Carnot batteries, which is supposed to show considerable development in the coming decade(s) and will probably become an important competitor for CHEST. Since CHEST is in fact a special type of a Carnot battery, all other types of such Carnot batteries are meant in this context when talking about competitors.

As was explained in Section 6.2.7, there are in principle a plenty of ways to realize the three different steps of such a power-to-heat-to-power storage. Accordingly, a range of system designs have been elaborated and partly also tested at laboratory or demonstration scale [Nov 2021] [Vec 2022]. The size, i.e. storage capacity and power, are supposed to be mostly similar to CHEST, i.e. in the MWh_{th} and MW_{el} range. Beside the input and output of electricity, also heat and in some systems also cold is taken up and/or delivered by the Carnot battery.

Given this range of possible system designs and similar key properties such as storage capacity, power and also efficiency, the other Carnot batteries are supposed to become strong competitors for CHEST. The selection of a certain Carnot battery will first of all depend on the boundary conditions of the envisaged application, for instance regarding available waste heat and cold as well as heat and cold demand and the respective temperature levels. Furthermore, electrical and thermal efficiencies and the LCOS will then be the main decisive parameters.

6.6. Competitiveness of CHEST

As was stated above, both electricity and thermal energy storage are competitors for CHEST, but EES are far more serious competitors than TES, since CHEST will never be only a TES and thus will always have some EES function. On the other hand, CHEST can in principle act as an EES only without taking (economic) advantage of the required heat input and the generated heat output. However, TES solutions should be taken into account in the competitor analysis, since together with another EES technology such as, for instance, a battery, they can also provide heat and electricity service like CHEST.

From the information given in the sections above, the following main conclusions on the competitors and the competitiveness of CHEST can be drawn:

- Flywheel energy storage (FES), supercapacitors and superconducting magnetic energy storage (SMES) are no competitors for CHEST, since these technologies normally have much lower storage capacities and above all lower response times, which enables them for applications of fast corrections of electrical imbalances CHEST is not suitable for.
- The main competitors for CHEST regarding the match of storage capacity and charging/discharging power are pumped hydro storage (PHS) and compressed air energy storage (CAES). Both technologies have the major disadvantage compared to CHEST that they have geographical constraints and thus will have a limited potential for the installation of further capacities. Concerning efficiency, CHEST is supposed to be

competitive with CAES and, given future development, also with PHS. The same can be concluded for the lifetime. The major disadvantage of CHEST at least at the current state of development must be seen in the higher (capacity-specific) investment costs. Thus, to be fully competitive with these bulk energy storage technologies PHS and CAES, CHEST needs to increase its efficiency and lifetime while simultaneously reducing CAPEX considerably.

- Hydrogen storage as well as most types of batteries are definitely also important competitors for CHEST. For the batteries, this is especially true for rather small-scale CHEST systems (1 MW_{el} or below), since CHEST will be advantageous in terms of CAPEX at high system sizes when taking into account the significantly lower lifetime of batteries. In terms of efficiency, CHEST cannot reach the level of batteries (in particular Li-ion type), but is competitive with hydrogen storage.
- Furthermore, other emerging types of Carnot batteries will very probably become strong competitors for CHEST, since they will address similar applications and might have similar characteristics. Compared to Carnot batteries using resistive heaters for the power-to-heat conversion, CHEST shows a higher roundtrip efficiency. Furthermore, the use of a combination of a latent and sensible heat storage is clearly an advantage compared to other Carnot batteries with subcritical Rankine cycles in terms of efficiency. However, the multitude of possible system designs for Carnot batteries and their currently low TRL do not allow a clear forecast of which designs will prevail – presumably several ones that fit for specific applications and boundary conditions in terms of electricity as well as heat and maybe also cold services (e.g. district cooling or for cooling of public buildings).

Table 7 lists some advantages and disadvantages of CHEST in comparison to other main EES technologies.

Table 7: Advantages and disadvantages of CHEST and its main EES competitors.

EES technology	Advantages	Disadvantages
CHEST	- no geographical constraint - high (theoretical) roundtrip efficiency	- currently high CAPEX - net heat requirement (when used as EES only)
PHS	- high lifetime - high technical maturity - relatively high roundtrip efficiency - very low self-discharge	- geographically limited to water reservoirs with different height above sea level - considerable land consumption and interference with the environment
CAES	- relatively high roundtrip efficiencies for AA-CAES	- geographically limited to underground caverns or tanks - not mature technology - relatively low roundtrip efficiency (for diabatic CAES)
Hydrogen storage (in particular, together with fuel cells)	- no geographical constraint	- relatively low roundtrip efficiency
Batteries	- no geographical constraint - high roundtrip efficiency	- relatively low lifetime - dependence on potentially scarce materials such as lithium

All in all, this analysis shows that there are already several relevant competitors for CHEST in place and further ones will probably follow. Despite this strong competition, CHEST will certainly have applications where it is the most appropriate and available storage solution.

7. Key messages

7.1. Introduction

This section is supposed to present and discuss some of the key messages that can be derived from the project results, the identified required progress and in light of the competitors that CHEST already has or is expected to have in the (near) future. These key messages are the result of dedicated discussions among the project partners in order to formulate the main conclusions of the project and show the perspective of CHEST in the years to come.

7.2. CHEST prototype vs. future real-size system

A first very important key message to deliver is the clear distinction between the CHEST prototype that was developed, built and tested in the CHESTER project and a future real-size CHEST system, for instance in terms of efficiencies but also regarding other aspects. The major objective of the prototype was the validation of the principal functioning of the CHEST technology. This first of all included ground-breaking advancements for the key components, i.e. for the high-temperature heat pump (HTHP), the Organic Rankine Cycle (ORC) and the high-temperature thermal energy storage system (HT-TESS), which in the CHEST system is a combination of a latent and a sensible heat thermal energy storage. Furthermore, these three technologies had to be connected to form a CHEST system, which was then experimentally tested by showing charging and discharging operation under several boundary conditions. With the build and testing of this prototype, the CHEST technology was lifted from TRL 3 to 5.

However, a future real-size system will have some major differences compared to the prototype, which is mainly due to the different technologies that will be used for a system in the MW_{el}-scale. First of all, turbomachinery technology will be used for such large-scale HTHPs and ORCs. For the prototype, it was not useful to use this technology, since this is not reasonable for a scale of only 10 kW_{el}. When it comes to the HT-TESS and in particular to the PCM storage, there is currently no experience on storages in the envisaged size of a future MW_{el}-scale CHEST system. However, it is quite clear that major changes in the storage design are appropriate.

So, to make it clear, there will be major technological differences in a real-size CHEST system compared to the prototype that was built in the CHESTER project. This has implications on, for instance, the efficiencies of the components and the roundtrip-efficiency of the system, but certainly also on the costs, as discussed below.

7.3. CAPEX and efficiencies: now and in the future

As was pointed out in Section 3.1, the main objectives of the further technological development of CHEST are the reduction of CAPEX and the increase of efficiencies. On the one hand, this will come with the scale-up of the system as was discussed above. On the other hand, further approaches to achieve this were presented in Section 3.2, such as the combination of the HTHP and ORC into one component or at least the shared use of major parts.

Table 8 shows what the project partners assess to be realistic numbers of the current and the future CAPEX of the main components. Both the current and the future CAPEX figures are estimates for an upscaled CHEST system. The figures do not include recent or future inflation. The future CAPEX figures can be achieved by the implementation of the suggested technological progress, see Section 3.

Table 8: Current and future CAPEX of the CHEST components.

Component	Current CAPEX	Future CAPEX
HTHP	350 €/kW$_{th}$	250 €/kW$_{th}$
ORC	1,000 €/kW$_{el}$	850 €/kW$_{el}$
LH-TES	100 €/kWh	50 €/kWh

As can be seen from this table, the lowest CAPEX reduction potential was identified for the ORC, which is due to the quite high maturity level of this technology. The highest CAPEX reductions are thought to be achievable for the LH-TES, which can mainly be done on the one hand by the selected PCM and on the other hand by the design of the heat exchanger. The SH-TESS is not listed in the table, since this is more or less standard technology and therefore, no significant CAPEX reductions are expected for this component.

Concerning the efficiencies, values for the main components and the complete system obtained from the simulations and the experimental testing were given in Section 2. As can be seen from the discussions there, different efficiencies can be defined for the system and the results highly depend on the assumed boundary conditions. Therefore, it is quite difficult to quantify efficiency figures for large-scale CHEST systems in the future considering the implementation of the technological improvement measures suggested in Section 3.

Making an estimate for the large-scale performance is not straightforward, so there will always be some uncertainty in the values. To make an estimate, the Fraction of Carnot found for larger scale ORC-systems by Öhman and Lundqvist [Öhm 2013] was used. This is the ratio of the actual cycle efficiency compared to the corresponding Carnot efficiency. The Fraction of Carnot depends on the system size, the chosen refrigerant, etc. However, assuming a Fraction of Carnot of around 45.0% seems acceptable. This would result in efficiencies for the upscaled ORC ranging from 9.3 to 11.7%, with an average of 10.7% (calculated based on the Carnot efficiencies during partial or full cycle tests of the CHESTER laboratory prototype). For the HTHP, the future efficiencies would be between 6.3 and 6.5, depending, of course, on the operating conditions. For the HT-TESS, higher efficiencies through better thermal insulation are a simple matter; with more space in the laboratory setting, this would have been implemented already in the CHESTER prototype. Therefore, a halving of losses should be simple, increasing efficiency to between 98.3 and 99.5%. With these estimations based on these current systems, roundtrip efficiencies, i.e. the product of the efficiencies of the main components HTHP, HT-TESS and ORC, in the range of 68% (= 6.4 * 10.7% * 98.9%) would be attainable.

The efficiency figures given above apply for a large-scale CHEST system with implemented technological progress measures as explained in Section 3, but for still using a passive latent heat energy storage concept and about the same temperature levels for the heat source of the HTHP, the melting point of the PCM and the heat sink of the ORC as used for the prototype. The melting temperature of the PCM in the prototype was 133 °C, the heat source temperature of the HTHP between 85 and 95 °C and the heat sink temperature of the ORC about 30 °C.

When applying other boundary conditions, e.g. higher heat source temperatures of the HTHP and/or lower heat sink temperatures of the ORC, also higher roundtrip efficiencies would be attainable.

7.4. Increased need for storage capacities

With the European Green Deal, the European Commission has set the climate and energy framework for the period until 2030. According to this European Green Deal, greenhouse gas emissions are supposed to be reduced by 55% compared to the emissions level of 1990. As a long-term vision, the EU aims at achieving climate neutrality by 2050 [EGD 2019].

In order to achieve these ambitious objectives in the ongoing decade and beyond, a massive increase of the installed capacities of renewable energy sources and a simultaneous phase-out of fossil fuel consumption have to be realized – both in the electricity and heat sector. Concerning the fluctuating renewable electricity generation from wind and PV, the installed capacity is expected to increase from 279 GW_{el} in 2017 to about 672 GW_{el} in 2030. In 2050, the installed wind and PV capacities are expected to account for 2,227 - 2,302 GW_{el} [ECA 2020].

However, electricity generation such as from wind and solar is mostly fluctuating and thus requires storage capacity in order to balance generation and demand and avoid the curtailment of the renewable energy generation. Even if there are further measures to use surplus electricity, such as load management, grid extension and the production of e-fuels for the transport sector, an increase of EES capacities is inevitable. The provision of thermal energy storage capacities is also important, on the one hand to increase energy efficiency and the use of fluctuating RES such as solar thermal, and on the other hand to allow for sector coupling, which arises from the increased share of renewable electricity.

For high shares of renewable electricity generation, required storage EES capacities will need to be considerably higher than what is currently installed. For instance, for a share of 89% of renewable electricity generation, an installed capacity of some 206 GW_{el} is expected for Europe [Ceb 2017].

If the electricity generation is completely covered by (fluctuating) renewables, as it is the objective for Europe for the year 2050, the required storage capacity will be even higher. According to a study published by the European Association for Storage of Energy, the required EES storage capacity accounts for 200 GW_{el} in 2030 and 600 GW_{el} in 2050. This requires an annual installation of storage capacities of about 14 GW_{el}/a until 2030 and of about 20 GW_{el}/a between 2030 and 2050, which is enormous given a currently installed total EES capacity in Europe of roughly 60 GW_{el}. Even if about 165 GW_{el} of the 600 GW_{el} required in 2050 will be covered by power-to-X technologies, there are still some 435 GW_{el} to be covered by power-to-X-to-power solutions [EASE 2021].

As was mentioned in Section 6.5, the PHS potential is limited to about another 30 GW_{el}, which together with the currently installed capacity results in a total installed PHS capacity in Europe in 2050 of roughly 80 - 90 GW_{el} [ECA 2020] There are also higher estimates of installed PHS capacities of up to 188 GW_{el} in Europe in 2050 [EASE 23-b], but even if this can be realized, there is still a considerable gap in required EES capacity.

Given these numbers, it is clear that additional storage capacities, in particular EES capacities, need to be installed in the coming decade(s). The currently dominating EES technology of PHS, as stated above, has only limited growth potential due to geographical limitations and the same is true for CAES technology. Further EES technologies such as batteries can and will have their contribution, but the availability of critical elements such as lithium, nickel and others that to a large extend are extracted outside the EU also limits the capacity growth potential of batteries. Thus, from an economic as well as strategic point of view, using batteries for really large-scale EES does not seem to be the most reasonable solution, but rather to focus the use of batteries on for instance mobile applications in vehicles.

CHEST is an EES solution that is not geographically constraint and is not limited to one key storage medium that could be critical concerning its availability. Furthermore, CHEST is more than EES by combining the heat and electricity sector by offering the possibility of integrating both renewable electricity and heat sources and generating both electricity and heat. Since CHEST can vary the heat and electricity output, it gives flexible storage capacity for the heat and electricity sector along with the respective demand.

7.5. Electricity-only vs. electricity and heat storage

Even though CHEST is a flexible energy management system combining the heat and electricity sector, the question is whether the future focus will be on applications where it uses this distinct feature or instead rather acts as an electricity-only storage solution. As was pointed out in Section 2.3.2, due to the inverse relationship between electrical and thermal performance, CHEST cannot maximize electricity and heat service at the same time. This means that when a CHEST system is designed or operates in such a way that it shows a high P2P ratio, heat output will be very limited and in most cases, CHEST will even be a net heat consumer. Vice versa, if CHEST is designed or operates in a way that maximizes the heat output, this will be at the expense of the electricity storage services of CHEST.

This perception of heat vs. electricity services is a key aspect to consider when discussing the future applications and business cases of CHEST, but has also implications on the design of the CHEST system, see Section 7.6.

On the one hand, CHEST could in principle be an electricity storage only, i.e. it would provide one or several of services such as regulation capacity, energy arbitrage or bill management and heat would only be relevant insofar as there is always enough available for the operation of the heat pump. The heat generated by the CHEST system would in this case have no (economic) relevance, probably even wasted to the environment to allow for a high P2P ratio and thus maximize CHEST´s economic profit from the electricity storage services. Concerning the system design, this will certainly mean that there is no use of a large low-temperature thermal energy storage (LTTES) to be connected with CHEST. If at all, a small heat storage on the heat source side can be integrated in order to guarantee HTHP operation in case that only fluctuating heat sources are available. As has been shown in Section 6, several applications and electricity services, respectively, were identified, but there are also strong competitors in place.

On the other hand, CHEST could be operated as both heat and electricity storage, i.e. both heat and electricity output would have an (economic) relevance. In this case, CHEST would probably be connected either to a DH network or directly to a specific end-user such as an industrial heat consumer. An LTTES can be reasonable in this application as a heat source and sink for the CHEST system and as a seasonal thermal energy storage for the DH system, but does not necessarily need to. Depending on the boundary conditions, CHEST would act as a flexible energy storage and management system here that effectively couples the heat and electricity sector. The P2P ratio would be lower compared to the electricity-only applications, but on the other hand, CHEST would require less heat, probably being a net heat generator. Competitors in this case would be both thermal and electrical energy storage technologies.

As a conclusion of the project results and the discussion among the project partners, both options, electricity storage only and electricity and heat storage, are thought to have a future relevance for CHEST with several applications identified. More details on this will be given in Section 8 of this report.

7.6. CHEST system design adapted to different applications

As was shown in Figure 1 and explained in Section 1.1, the CHEST system consists of an HTHP, an ORC and an HT-TESS, which in turn consists of an LH-TES and an SH-TESS. The HTHP takes up electricity and low-temperature heat to charge the HT-TESS via two heat exchangers: the LH-TES via its condenser and the SH-TESS via its subcooler. The heat stored therein is then used to drive the ORC, i.e. heat is transferred from the SH-TESS via the preheater and from the LH-TES via the evaporator to the ORC cycle. The ORC generates electricity and low-temperature heat that is transferred e.g. to a DH network, to an industrial heat consumer or to the environment. Furthermore, CHEST can be combined with an LTTES.

In principle, as was partly discussed above, there are different possibilities to adapt CHEST´s system design and operation to different applications:

(1) As said above, an LTTES can be part of the system or not.
(2) The SH-TESS could be removed. Instead, heat could be directly integrated via the subcooler and the preheater.
(3) The LH-TES could be removed, i.e. there would only be a sensible heat thermal energy storage system with preferably pressurized hot water as the storage medium, and this SH-TESS would take up all the heat from the HTHP and deliver heat to the ORC, see also Section 3.2.2.
(4) The HT-TESS could also be charged directly with high-temperature heat from a respective high-temperature heat source instead of using a heat pump.
(5) High-temperature heat could also be taken from the HT-TESS in order to supply a consumer with heat required at such a high temperature level.

Figure 10 shows a schematic of a CHEST system with the five abovementioned measures indicated by the blue numbers () in the figure.

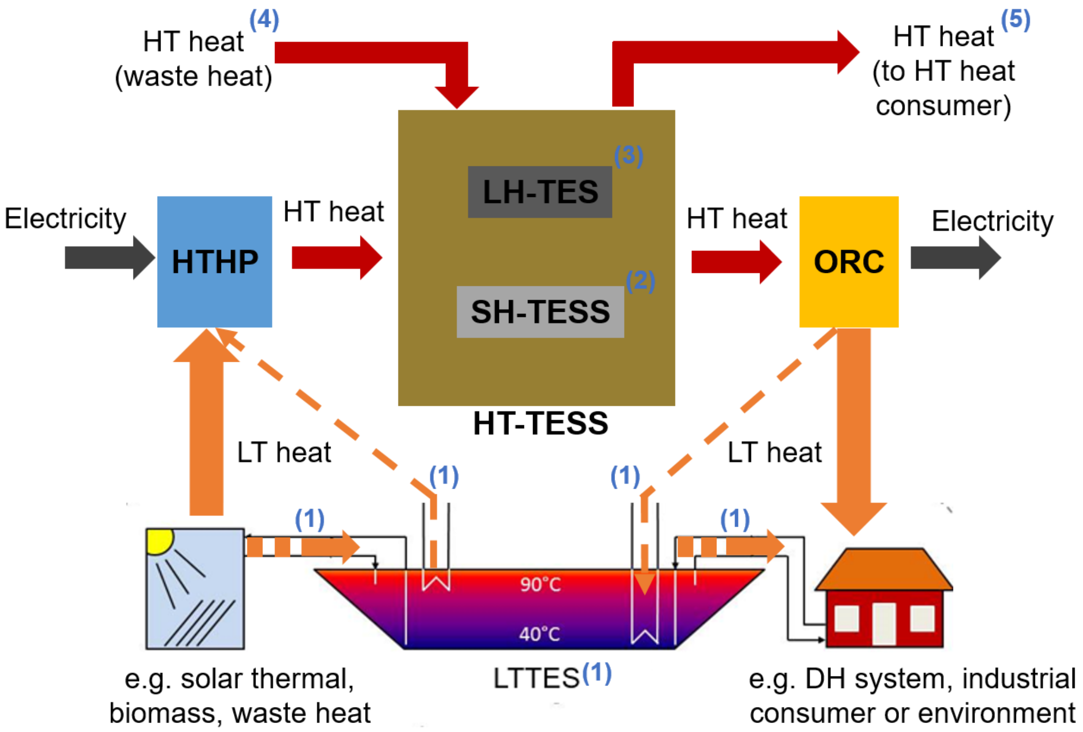

Figure 10: Schematic of possible CHEST system design and heat integration possibilities; numbers in blue refer to the measures listed above.

The abovementioned possibilities can in principle all be realized, and for the one or the other application they will have specific advantages and disadvantages. However, it is very important to be clear about the definition of a CHEST system, i.e. which of the abovementioned options would still be called a "CHEST system" and which would not. On the one hand, this is helpful for the communication and explanation of what CHEST is. On the other hand, this is also essential in the distinction of CHEST towards other energy storage options, in particular towards other types of Carnot batteries. In order to clarify this definition of CHEST, dedicated discussions among the project partners were carried out with the following answers found:

<u>LTTES as part of a CHEST system:</u>

The LTTES does not belong to the CHEST system itself, but, as was said above, it can be combined with a CHEST system. This is indicated by the number (1) in Figure 10 showing the LTTES as a component and also its heat integration with CHEST. In this case, the LTTES takes up (renewable) heat from e.g. solar thermal, biomass or waste heat, and stores this heat to make it available for e.g. a DH system, but also as heat source for the HTHP. Furthermore, the LTTES can be the heat sink for the ORC, but does not necessarily need to; the ORC heat can also be transferred to the environment despite the existence of the LTTES.

SH-TESS and LH-TES as part of a CHEST system:

In principle, only one storage would be enough to run the system and the other one could be removed, as is indicated in Figure 10 by the number (2) for the SH-TESS and number (3) for the LH-TES. As was proposed in Section 3.2.2, using only a pressurized hot water storage would simplify the system and thus reduce CAPEX considerably. However, this would also decrease the efficiencies of the HTHP and ORC cycle. Furthermore, with using only a pressurized hot water storage, CHEST would lose a key characteristic in the distinction towards other Carnot batteries, since then, it would just be heat pump + storage + ORC with no special characteristic of differentiation.

As a consequence of this, CHEST can be defined as follows: it consists of a **HTHP** and an **ORC**, both using **subcritical Rankine cycle**, and to match these two Rankine cycles, a **combination of latent and sensible heat thermal energy storage** is required in order to achieve high cycle efficiencies. Thus, it is exactly this combination of latent and sensible heat thermal energy storage, which makes the CHEST system a unique type of a Carnot battery.

In principle, also direct heat integration could replace the SH-TESS, but it is essential for a CHEST system that sensible and not only latent heat is delivered to the ORC and to do so, it is reasonable to store the sensible heat from the heat pump cycle. This means, some kind of sensible heat is an inevitable part of a CHEST system beside the latent heat.

Integration of HT sources and consumers:

As indicated in Figure 10 by the number (4), the HT-TESS can also be charged directly with high-temperature heat instead of using the heat pump. In case of CHEST, both the LH-TES and the SH-TESS could be charged. In fact, this can be a reasonable option for one of the two storages if they were charged unevenly. Furthermore, this increases the P2P ratio since no electricity is required for the charging process.

The HT-TESS can also directly deliver high-temperature heat to a respective consumer, as is indicated by number (5) in Figure 10. This decreases the P2P ratio of the CHEST system, but can be reasonable if the low-temperature heat from the ORC is not usable for this consumer because of the too low temperature level.

To make it clear, the integration of HT sources (4) and consumers (5) is an option, but it does not replace the HTHP and/or the ORC. As was said above, the HTHP and the ORC are clearly a part of the CHEST system. Thus, charging and discharging of the HT-TESS will mainly be carried out via the HTHP and the ORC. Where appropriate, this integration of HT sources and consumers can be an additional option for charging and discharging.

8. CHEST´s future perspectives

8.1. Introduction

From a very general point of view, CHEST, like every other electrical or thermal energy storage, lives on the uptake and supply of energy, i.e. the use of surplus energy generation or the shift of loads from hours of high to hours of low energy demand. This energy storage needs to have some economic value/benefit, be it through the generation of payments (revenues) or through cost savings. This in turn can be achieved by the reduction of the size of other energy generators, the increase of energy generation of fluctuating renewable energy sources, grid stabilization, etc. Unless an energy storage solution is used as seasonal storage, it will be decisive for the economic viability of the storage, that there is frequent charging and discharging and the uptake of energy is for free or cheap or even generates revenues and the sale of energy is carried out at high energy prices.

Given the current status of CHEST, the presence of competitors and the key messages that were formulated in Section 7, the following shall discuss what this means in terms of:

- the relevance of CHEST in the future European energy system
- the most promising applications and respective business cases.

Beside the pure economic perspective, also other aspects such as energy security, environmental impact and strategic implications need to be taken into account here.

8.2. Relevance of CHEST in the future European energy system

The further increase of renewable energy sources will soon imply the need of massive intervention to retrofit and revamp the existing transmission and distribution grids. Higher amounts of energy will be dispatched from distributed renewable production clusters to the aggregates in municipalities, industrial districts, etc., that will perform as both consumers and producers (i.e., prosumers) of energy. The electric grids will face a pronounced transition towards digitalization and the optimized management of bi-directional energy fluxes. Many portions of the grid may not be ready for this challenge. Technical interventions to reinforce the weaker sections of the grid may be very expensive for the TSO/DSO and, hence, for served communities. However, they will be fundamental to ensure the smart and resilient operation of the grid, avoid renewable energy curtailment, and guarantee a high level of service.

As an alternative to the massive reinforcement of the grid sections that are not able to dispatch and properly manage such amounts of energy, solutions for the storage, conversion and time-shift of renewable energy are available as well. CHEST offers such a storage solution and thus may accomplish this task avoiding the need for DSO/TSO to reinforce the grid or at least reducing the extent of grid reinforcements.

As discussed before, pumped hydro storage (PHS) is currently the most diffused technology for the storage of electricity in the EU as well as worldwide. Alternatives are in principle available, but at such large storage capacities like pumped hydro, CHEST could be a favorable option thanks to the fact that its operation is independent from the geographical location (in contrast to PHS and CAES) and cheaper than using batteries. Furthermore, CHEST will be a storage solution with less environmental impact than PHS, once a suitable PCM is found for the latent part of the HT-TESS.

As a consequence, CHEST is thought to be mainly relevant for this further increase of bulk electricity storage. In this field, CHEST is a competitive technology and there is a clear need for the increase of capacities to guarantee energy security. Thus, CHEST is assessed to get its share of these capacities to be installed.

The feasible potential capacity of installing CHEST systems in large scale in the EU is found to be in the range of 30 GW_{el}. This is, however, in a highly competitive market where CHEST only operates on electricity markets. The potential within combined systems that operate on electricity and heat markets is lower, but likely with a larger possible revenue. In the near future, district heating is also expected to be developed, as a renewable energy enabler, and will need to grow significantly to cover a higher share of the heating and cooling demand [HRE 2018]. This gives more opportunities to implement CHEST systems. The potential in this context is found to be in the range of 10-15 GW_{el}.

8.3. Promising applications and business cases for CHEST

The main purpose of a CHEST system being a power-to-heat-to-power storage is the uptake of excess (renewable) electricity and the supply of electricity at a later point in time when electricity demand exceeds electricity generation. Due to this, CHEST applications and dedicated business cases are particularly those that are relevant for other EES technologies. Since a CHEST system generates low-temperature heat in the ORC, also this heat supply can be part of a business model. However, as was mentioned above several times, some aspects have to be considered in this context.

First of all, it has been shown that in particular in cases with a high P2P ratio of the system, CHEST is a net heat consumer. This means, more heat is required for the HTHP operation than the ORC produces. Thus, from heat perspective, such a CHEST operation does not mean a revenue, but additional costs. Whether it means revenues or costs also depends on the temporal distribution of the heat consumed and delivered by CHEST, by the temperature levels and the prices paid for the heat. Furthermore, due to the competition between heat and electricity output described in Section 2.3.2, a maximization of the heat output will inevitably occur at the expense of the electricity output.

Since the sale of electricity normally means higher revenues than the sale of heat (at least per kWh), business models with pronounced focus on heat supply are not very reasonable. Furthermore, if the focus of CHEST was only on heat storage, it would definitely not be competitive to other heat storage solutions such as (pressurized) hot water storages.

Another point to consider is that a maximization of CHEST´s heat output means that a high share of the renewable electricity taken up by the heat pump has been transformed into heat. However, if in principle the main purpose of CHEST is a power-to-heat application, there are much simpler and cheaper technologies than CHEST on the market (electrical heater or only the heat pump) to realize this. As a conclusion, the operation of CHEST with a low P2P ratio in order to maximize heat output must be evaluated as only temporarily reasonable, for instance during winter months when heat demand is high.

As has been discussed before, CHEST offers possibilities to adapt the P2P ratio and thus the electrical and thermal output of the system, which means flexibility concerning offering both electricity and heat services whenever the one or the other promises a higher profit. So, as an overall conclusion, heat supply can be part of a business model, but in contrast to an electricity service, heat service will definitely not be a stand-alone reason and business model for a CHEST system. However, looking at the economic analyses made in the CHESTER project, a single electricity service might also not provide economic viability, which is mainly due to the still too low remuneration for electricity storage combined with the high CAPEX of CHEST.

As a consequence of the aforementioned aspects, CHEST will achieve economic viability if it provides one or perhaps rather several electricity services, and additionally, its heat integration can also be utilized economically. This leads to the following applications and respective business models that were identified to be the most promising ones for CHEST (sorted by relevance):

1. <u>CHEST as a heat and electricity storage solution providing aggregated services, in particular for industrial energy producers and consumers:</u>

Despite the higher significance of electricity storage service, the application of CHEST as a heat and electricity storage is the most promising application as pointed out above. However, CHEST´s economic viability will require specific boundary conditions.

To provide aggregated services means that CHEST somehow profits from the uptake and generation of heat and electricity under respective boundary conditions, i.e. with several generators and consumers of heat and electricity present. This can for instance be an industrial park, an energy community, or a certain district of a city connected to the CHEST system via a DH system. For the stakeholders in this environment, the uptake of electricity by CHEST can be useful, since it increases the yield of their own renewable electricity sources such as wind or PV and thus avoids curtailment. The uptake of heat can be useful for them when it is waste heat that otherwise would mean costs for coolers. This is especially relevant for industrial heat sources (available waste heat). The generated heat on the other hand can for instance be fed into a DH system to supply customers with heat demand. Furthermore, the uptake and generation of electricity by CHEST can be used to reduce peak electricity loads.

Since heat and electricity storage is relevant here and the business case can comprise a range of stakeholders, the situation can be much more complex than for an electricity-only use case. However, this is exactly a case CHEST was actually thought of: to adapt heat and electricity input and output dependent on the needs of the RES generators and consumers and to couple the heat and electricity sector, thus operating as a smart and flexible energy management system.

The analyses carried out in the CHESTER project showed that in particular the use of a CHEST system in an industrial environment is a promising application. One reason for this is the economic utilization of the uptake of waste heat, i.e. industrial waste heat producers will pay to get rid of the waste heat. In contrast to that, the connection of CHEST with a DH system is less promising. In particular, when the CHEST system is a net heat consumer, there will probably be no or very low economic benefit with the heat integration in such a case.

2. CHEST as an electricity storage only, providing several grid services:

Given the pronounced significance of CHEST as electricity storage discussed above, CHEST could also operate as electricity storage only contributing to the balancing of the electricity grid in different ways. As was stated in Section 8.1, bulk energy storage is a field where CHEST is expected to be advantageous compared to other technologies such as PHS and CAES due to their geographical limitations. However, the respective business model for this would be energy arbitrage, which was found to be uneconomic. Therefore, CHEST needs to provide other grid services like tertiary regulation power, perhaps in the future also secondary regulation power under the assumption that start-up times of the HTHP and ORC can successfully be reduced. Since the provision of regulation power will probably not be economically viable alone, CHEST certainly needs to be active in more than one electricity market.

Furthermore, CHEST can contribute to the grid´s stability and economically profit from this by services like congestion relief or transmission and distribution investment deferral. Also here, a single business model might be not enough to provide economic viability.

Moreover, it is important to stress that in such an application where CHEST operates as an electricity-only storage, CHEST needs to get its required heat for free or at a very low price.

3. CHEST as a heat and electricity storage solution in island energy systems:

Similar to the aggregated services described above, CHEST is also assessed to be useful in an island energy system, i.e. a location that is not connected to the electricity grid. The main focus in such an application lies in the uptake of surplus electricity in order to cover electricity demand at any time, even when there is no electricity generation for instance by PV or wind. Depending on the boundary conditions, the heat integration can have a different relevance, but will certainly be less significant than the electricity storage due to the missing electrical grid connection. Since CHEST has a certain start-up time of the HTHP and the ORC, it might be combined with another type of EES (e.g. batteries), but with considerably lower capacity, in order to bridge the time it takes for CHEST to start its operation.

The business case in this application is to reduce overall energy costs for the location of this island energy system.

4. CHEST as an electricity storage only, linked to RES plants:

CHEST can also be used in direct vicinity of a large renewable electricity generator such as a wind farm or a larger PV plant. The main business case would be to shift the generation from times with low prices to times with high prices. In principle, CHEST could also be used to avoid curtailment. However, with the regulation currently in place in the EU, curtailment is remunerated anyway. Thus, CHEST would mean no additional economic profit.

9. Conclusions

A CHEST system is an innovative energy storage and management system that couples the heat and the electricity sector by storing surplus renewable low-temperature heat and electricity in the form of high-temperature heat and generating low-temperature heat and electricity at times with increased energy demand. From a technological point of view, the key characteristics of this power-to-heat-to-power system are on the one hand the use of subcritical Rankine cycles for both a high-temperature heat pump (HTHP) as the power-to-heat part and an Organic Rankine Cycle (ORC) as the heat-to-power part. On the other hand, there is the high-temperature thermal energy storage system (HT-TESS), which is a combination of a latent heat thermal energy storage (LH-TES) and a sensible heat thermal energy storage system (SH-TESS) in order to match the two Rankine cycles and provide a high roundtrip efficiency. This combination of latent and sensible heat thermal energy storage is also a unique feature of a CHEST system.

A first-of-its-kind prototype of such a CHEST system with a charging and discharging power of about 10 kW_{el} was developed, built and successfully tested in a laboratory environment. With this constructional and experimental work, the operation of a CHEST system was clearly validated and CHEST technology lifted from TRL 3 to 5. Furthermore, comprehensive theoretical analyses including simulation studies, elaboration of business cases and a life cycle analysis were carried out in order to provide a comprehensive techno-economic assessment of this technology and formulate its future perspectives in commercial applications.

The theoretical and experimental work carried out clearly showed which progress and which actions are required in the coming years to bring CHEST technology to this commercial status. From a technological point of view, a scale-up from the order of magnitude of 10 kW_{el} up to several MW_{el} has to be carried out, which will require demonstration projects with CHEST system sizes in between to show CHEST operation in real environments. The most important objectives of the technological progress are definitely the reduction of CAPEX and the increase of efficiencies. This can mainly be achieved by the use of turbomachinery for the HTHP and ORC and changes in the material selection and design of the HT-TESS. Furthermore, the scale-up of the LH-TES and the realization of an active storage concept for the LH-TES are essential aspects of the further technological development of CHEST.

However, even if considerable improvements in CAPEX and efficiencies are achieved by the abovementioned measures, the operation of a CHEST system will be challenging in terms of providing economic viability. First of all, there are several competing technologies for electrical and thermal energy storage already in place, such as PHS, CAES and the different types of batteries. Further emerging technologies such as other power-to-heat-to-power systems (so-called “Carnot batteries”) will also likely compete with CHEST in the future. Furthermore, the remunerations for the electricity and heat storage services provided by CHEST, for instance through the participation in electricity markets or through the sale of heat, are found to be generally rather low compared to the CAPEX at the moment. As a consequence, it is currently very difficult for CHEST to achieve economic viability. In the future, the evolution of market prices as well as the reduction of further financial burdens such as taxes are thought to be the key for an economic operation of CHEST. However, very probably, CHEST will not achieve economic viability with a single electricity or heat service, but will have to be active in different (electricity) markets.

Concerning future applications and business models, the focus is supposed to be in two directions:

- On the one hand, CHEST will be used as heat and electricity storage providing aggregated heat and electricity services mainly for industrial end-users[1]. The integration of CHEST with DH systems is thought to be of less significance. When providing aggregated heat and electricity services, CHEST can really show its advantages as a smart and flexible storage solution coupling the heat and electricity sector. In this context, CHEST can be a valuable tool for the decarbonization of the industrial sector.
- On the other hand, CHEST will be used for large-scale electricity storage with heat playing a minor role, if at all, i.e. CHEST is more or less used purely as electricity storage. In this application, CHEST will provide several electricity services such as energy arbitrage, tertiary response or congestion management. Being used as such a large-scale electricity storage, CHEST is thought to be an important element of taking the challenge of the required massive increase of EES capacities in the EU until 2050.

Despite the currently very difficult (and also in the future rather challenging) economic viability of CHEST, this technology is thought to play a vital role in Europe´s energy supply systems. This is mainly due to the expected massive increase of fluctuating renewables, particularly in the electricity sector, which consequently requires a considerable increase of EES capacities. This increase of EES capacities cannot be provided by PHS and CAES since their potential of further plant installations is geographically limited. From a strategic, but also environmental point of view, batteries such as lithium-ion or lead-acid, are also not a suitable solution for providing large-scale EES due to their use of scarce or critical materials.

Perhaps, other types of power-to-heat-to-power systems ("Carnot batteries") can also provide these required large storage capacities and thus could be strong competitors for CHEST. However, at the moment, these Carnot batteries show a similarly low TRL as CHEST and it is difficult to forecast which of the different types and configuration will prevail in the future. As a consequence of this, it is reasonable to invest major R&D capacities in the further development of such power-to-heat-to-power-systems including CHEST in order to have these systems available in the coming decade(s) in order to provide a secure and decarbonized energy supply throughout Europe.

[1] This applies to industries with thermal processes on a temperature level up to the melting temperature of the PCM in the LH-TES, which for the CHESTER prototype was 133 °C and in the future could be up to 250 - 300 °C. In principle, CHEST can take up heat on even higher temperature levels, i.e. via direct charging of the HT-TESS, but this is rather an option for CHEST, see Section 7.6. The main heat input to CHEST should be low-temperature waste heat for the heat pump, and this will be supplied at a temperature level of about 50 - 100 °C, in the future (with PCMs having higher melting temperatures) maybe up to 150 °C. Thus, the focus is clearly on industrial end-users having available waste heat up to this temperature level. Concerning the heat production of CHEST, the maximum temperature level that CHEST can provide heat at is the melting temperature of the PCM (minus some °C lost for the heat exchange). However, as pointed out in Section 7.6, the direct supply of such HT heat taken from the HT-TESS is also rather an option for CHEST, and not the main purpose. Instead, the main amount of heat provided by CHEST is low-temperature heat generated at the condenser of the ORC. This heat will mostly be at a temperature level of about 30 - 60 °C, perhaps also a bit higher in the future.

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