CHESTER

Compressed Heat Energy
Storage for Energy
from Renewable sources

Development of business models

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Glossary, abbreviations and acronyms

CAPEX	Investment cost
aFRR	Frequency restoration reserves with automatic activation
COP	Coefficient of Performance
DH	District Heating
DSO	Distribution System Operator
El	Electric energy
ENTSO-E	The European Network Of Transmission System Operators For Electricity
EU	European Union
FCR	Frequency containment reserve
GLAS	GreenLab Skive
HP	Heat Pump
IN	Imbalance netting
IRR	Internal Rate of Return
KPIs	Key Performance Indicators
Low-T	Low Temperature
LTES	Latent Thermal Energy Storage

mFRR	Frequency restoration reserves with manual activation
O&M	Operation and Maintenance
OPEX	Operation cost
ORC	Organic Rankine Cycle
PHES	Pump Hydro Energy Storage
PHS	Pumped Hydro Storage
PTES	Pit Thermal Energy Storage
PtP	Power-to-Power
PV	Photovoltaic
RES	Renewable Energy Sources
ROI	Return of investment (time)
RR	Replacement reserves
Th	thermal energy
TSO	Transmission System Operator

1. Introduction

1.1. Executive Summary

This deliverable presents the outcome of the final economic assessment for the commercial application of the CHEST technology with the emphasis of future market conditions. The analysis presented in this report is also built upon the knowledge drawn from previous economic assessments of the CHEST technology in the project (refer to connected deliverables mentioned in chapter 1.5).

CHEST system having both functionalities as thermal and electric storage has been at first globally analyzed for its suitability at current and incoming energy markets, and competition with other storage technologies. From a balancing services perspective, the 15-minutes minimal response time of the CHEST system makes it capable for participation in Replacement Reserve (RR) and Imbalance services (IN), and to some extent also in mFRR. From the economical point of view CHEST has currently significantly higher costs than other technologies. The cost of the CHEST plant is expected to gradually reduce over the years as the HP and ORC components should get integrated and cost of the latent storage based on PCM materials will potentially halve. Moreover, the CHEST system has advantages over other storage technologies from the technical point of view such as:

- is more compact for the same electric capacity,
- has more stable operation over time (does not lose efficiency over years),
- has functionality of both thermal and electric storage,
- does not depend on geographical features,
- can be used as seasonal storage.

Conclusions of the earlier financial assessments for the CHEST business models (please refer to related deliverables listed in section 1.5) helped to identify three potential applications for the CHEST system. These main conclusions include

- the CHEST system needs to be utilised as long as possible during a year with the maximum capacity it has been sized to;
- the storage cost is the main issue with achieving the profitability of the investment using the CHEST system;
- the CHEST system will perform more cost-effectively at future fuel, heat and electricity prices based on the available projections in different countries;
- successful implementation of the CHEST system requires changes to the energy policy and regulations;
- the investment cost if the CHEST system needs to reduce which is envisaged in nearest future given continuous development of the CHEST components and competitiveness between their suppliers.

The three potential business models that have been identified with highest potential towards the deployment of the CHEST system in the future market are the following:

(1) CHEST as a provider of aggregated services in a minigrid, this means providing flexibility for heat and electricity storage and use
(2) CHEST providing the same services as Pumped Hydro Storage (PHS)
(3) CHEST as an alternative to DSO investment for grid reinforcement

And their key results are summarized as follows:

(1) CHEST - as a provider of aggregated services in a minigrid – this means providing flexibility for heat and electricity storage and use, where focus is on thermal side of the system, the CHEST is used to offset fossil fuel consumption for heat production to the industrial consumers; moreover excess steam heat otherwise dissipated with cooling plant is used as heat source to the CHEST heat pump which in return provides cooling at no cost; electricity production and consumption of the CHEST is settled using electricity tariffs for industrial partners and electricity bought to run heat pump is discounted with a tax exemption on electricity used for process heat.

This business model in which the CHEST system has been integrated within a complex energy system was concluded to represent one of the potential applications of the technology. The specific case study that has been used to analyze this potential business model shows that interesting results can be achieved, with return of investment within 5–6-year of the project lifetime. This is though based on a fixed historical average electricity price from Denmark, no need for the sensible storage (part of the HTTES) and given both heat pump and ORC turbine can run in parallel giving long operation hours.

(2) CHEST vs. PHS – here the CHEST system is analyzed as a competitor to PHS and potentially becoming an alternative of electric storages with capacity between 1 MW and 100 MW. It was analyzed as in direct connection to the power grid or adjacent to the RES power plant such as PV. The study also looked at different operation strategies taking advantage of cheap electricity sources from the RES and selling electricity produced in the ORC at hours of the highest electricity demand and thus the highest electricity prices.

The CHEST concept is still more expensive than PHS technology, though, in the performed economic study neither system gives a return of the investment within the 30 years project period. The CHEST system allows, however, for energy storage with no restrictions to the location and is one of very few alternatives to PHS which could drive prices reduction of storage technologies in the future electricity markets.

(3) CHEST as an alternative to DSO investment for grid reinforcement – serves as “stop-and-go” (time-shift) solution serving a new large-size renewable power plant. The CHEST storage is aimed here to tackle and avoid curtailment of the excess electricity production from the new coming RES plants at the time of peak production. The results of the business model were compared with the alternative solution of reinforcing a certain portion of the distribution grid (i.e., the branch connecting the power plant to both the transmission grid and the local consumption nodes). From a 'macro' perspective this applies too to the TSO interconnection grids between countries. It depends on the country but there could be some conflict of interest regarding the need of having a minimum quota of interconnection and the curtailment reduction locally applied. This is not analyzed in this study.

The reference case study assesses the profitability of a 10/5-MW (HP/ORC) CHEST system used to store energy from a 50-MW PV plant, considering:

- the 2019 spot electricity price[1] in Italy;
- a minimal congestion level of the national grid (20%, referred to PV size; i.e., 10 MW);
- two economic scenarios for grid reinforcement costs.

In this reference case, the investment in CHEST technology is more profitable than grid reinforcement when the branch length to be retrofitted is higher than 190 km (in the most costly scenario for the reinforcement). A sensitivity analysis was carried out considering instead a 5-MW PV plant, highlighting a heavy improvement of the CHEST investment IRR along with the increase of both electric energy price and the congestion level of the grid. Keeping the same congestion level as above (20%), CHEST system results to be more profitable when the length of the reinforced grid is higher than 16-19 km. ~~B~~

1.2. Purpose and Scope

The purpose of this deliverable is to identify and analyze business models with the application of the CHEST technology placed in the new market's mechanisms. The case studies have been defined using experience from earlier work done in the project and pointing out in direction of the most promising solution. The opportunities of the CHEST system have been sought by analyzing its suitability at heat and electricity markets and comparing with alternative energy storage technologies. A feasibility study has been undertaken for either more complex system offering aggregated services for industry or targeting flexibility users (RES producer, DSO, TSO). Potential competition to a pumped hydro plant integrated in a DH system is also assessed which is to identify a potential replacement for the PHS electricity storage technology which currently plays monopoly at large capacities range. The report also reviews the electricity markets in general to identify the one, for which the CHEST system could become a potential user.

1.3. Methodology

The economical assessment of the identified business cases mentioned in Executive Summary is run in form of cash flow analysis (not-discounted) for a 30-years project period. This is done given investment and operation costs of the CHEST system [10], [20] compared with the reference which depends on the case study (1-3) and results with KPI, IRR or/and ROI. Case study (1) is based on the example site in Denmark while (2) and (3) were built sourcing data from the Italian energy systems. Therefore, different local historical electricity and heat prices and taxes are applied. The sensitivity analysis is performed by changing

(1) CAPEX, OPEX, electricity prices.
(2) HP COP, ORC efficiency, electricity prices.
(3) CAPEX, OPEX, grid constrains, electricity prices.

[1] The profiles after 2020 were not considered due to significant variations caused by COVID-19 pandemics. moreover, future electricity price projections are more favorable to CHEST-system, given their high fluctuations (these have been analyzed in D6.2, D4.5 in order to improve the economy of the CHEST application using historical electricity price data) hence current deliverable is built upon a pragmatic approach aiming at identification of business model for the CHEST system even in with unfavorable electricity price profile.

1.4. Structure of the document

The report begins with Chapter 2 the review of the current and future heat and electricity markets focusing on identifying those suiting the CHEST services. The CHEST system is also compared with other competing heat and thermal storage technologies.

Then, in Chapter 3 three individual business models for the CHEST technology compared with a reference currently existing system are evaluated with the aim of concluding how this could be profitable and under which conditions. This consist of

- Chapter 3.1. CHEST as a provider of aggregated services in a minigrid,
- Chapter 3.2. CHEST vs. pumped hydro and
- Chapter 3.3. CHEST as an alternative to DSO investment for grid reinforcement.

Lastly, in Chapter 4 the conclusions of the analysis are summarized.

1.5. Relations with other deliverables

There are a few project deliverables which this report has a close relation to, and these are spread over a couple of work packages.

- WP2 – D2.2 (Task 2.2) [22] – HP COP and ORC efficiency range analyzed in the technical analysis based on TRNSYS model and simulations of this task was used in case study (3).
- WP2 – D2.3 (Task 2.3) [23] – ORC power range analyzed in the technical analysis based on TRNSYS model and simulations of this task was used in case study (3).
- WP4 – D4.5 (Task 4.3) – Deliverable was used as source of experience with the economical viable and inviable business cases and allowed to draw productive conclusions and define new business scenarios (1), (2), and (3) in the right direction.
- WP6 – D6.2 (Task 6.2) [24] – the starting point for the investment and operation costs for the CHEST system in all cases (1-3) have been sourced from this deliverable, however the costs both for current technology and future reduction in cost were first updated during the project by the CHESTER consortium (Ugent, Tecnalia, DLR) in March 2022 and then revised in May 2022. Deliverable was also used a source of experience with the economical viable and inviable business cases and allowed to draw productive conclusions and define new business scenarios (1), (2), and (3) in the right direction.
- WP6 – D6.5 (Task 6.5) – technical specification for the HP and ORC was used for case study (1) to select the unit with right parameters working with the waste heat source (70 °C) used in this study.

2. Energy market and opportunities for the CHEST system

This section presents a general overview of both electricity markets and energy storage competitors giving a better understanding of where the CHEST system could potentially find an application.

2.1. Current energy markets

The study concentrates on future mechanisms and energy markets. To do so, a starting point of the analysis should be made at current ones to understand which already exist and how the CHEST system could fit in today, and then look for the alternative planed mechanisms in order to both, see if they create a potential for the CHEST, or otherwise if they could be adjusted.

By suiting the market is meant that the CHEST system has a profitable business case, and this can be achieved through selling its services expected at these markets. Whether the CHEST plant can participate in them is mostly a matter of the sufficiently fast responsiveness (i.e., the time from the moment the system receives a control signal till it rumps the capacity up or down to the requested output). The markets and the respective services for both, the present and the future, evolving markets and more flexible CHEST technology are shown in Table 1. The majority of applications are expected at purely electrical markets, on balancing market and day-ahead market at current conditions and most of others in future markets (refer to part titled Electricity of Table 1 and see more in subsection 2.1).

The pure heat energy systems have cheaper alternatives such as steel tanks or seasonal storage (e.g. PTES), moreover, the intention of designing the CHEST technology is to use it for supplying complex energy systems like industrial parks which work as a synergy. These consist of multiple users which do not only consume heat and electricity but also generate excess energy as their side product or have RE based energy production (refer to part titled Heat of Table 1 and see more in chapter 3.1). These energy hubs could potentially benefit of CHEST system which allows for storing both heat (and even low and high temperature heat) and power.

Table 1 Possible applications of CHEST System in the next future scenarios/energy markets .

<table>
<tr><th rowspan="2">Energy output</th><th rowspan="2">Market</th><th rowspan="2">Service</th><th colspan="2">Applications</th></tr>
<tr><th>Current</th><th>Future</th></tr>
<tr><td rowspan="11">Electricity</td><td rowspan="4">Electrical grid services</td><td>Frequency regulation</td><td></td><td>X</td></tr>
<tr><td>Secondary reserve</td><td>X</td><td>X</td></tr>
<tr><td>Tertiary reserve</td><td>X</td><td>X</td></tr>
<tr><td>System restoration (i.e. black start)</td><td></td><td></td></tr>
<tr><td rowspan="2">Electricity market</td><td>Day ahead + intraday market</td><td>X</td><td>X</td></tr>
<tr><td>Local peer-to-peer market</td><td></td><td>X</td></tr>
<tr><td rowspan="3">TSO network / DSO network</td><td rowspan="2">Investment deferral to transmission / distribution infrastructure (see chapter 3.3)</td><td></td><td>X</td></tr>
<tr><td></td><td>X</td></tr>
<tr><td>Storage hybridization: Extra service to fast responding storage systems that can access higher value markets (see chapter 3.3)</td><td></td><td>X</td></tr>
<tr><td rowspan="2">RES</td><td>RES support / integration (see chapter 3.2)</td><td>X</td><td>X</td></tr>
<tr><td>Colocation with variable renewables</td><td>X</td><td>X</td></tr>
<tr><td rowspan="3">Heat</td><td rowspan="2">Heating</td><td>Heating services</td><td></td><td></td></tr>
<tr><td>RES support / integration</td><td></td><td></td></tr>
<tr><td>Process heat</td><td>Industrial parks (see chapter 3.1)</td><td>X</td><td>X</td></tr>
</table>

2.1. Future energy markets

Given the European power system is transforming 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 which the CHEST system is a great example.

European TSOs use different processes and products to balance the system and restore the frequency, based on historic developments and different balancing philosophies. Balancing energy in Europe is organized in up to five steps as shown in Figure 1 [21]. The suitable services which can be provided using the CHEST systems are also marked in the picture given its response time, frequency level and resilience of supply.

From a balancing services perspective, the 15-minutes minimal response time of the CHEST system makes it capable for participation in Replacement Reserve (RR) and Imbalance services (IN), and to some extend also in mFRR. The other two services of the balancing market, i.e., Frequency containment reserve (FCR) or Frequency restoration reserves with automatic activation (aFRR) certainly are not dedicated for the CHEST technology.

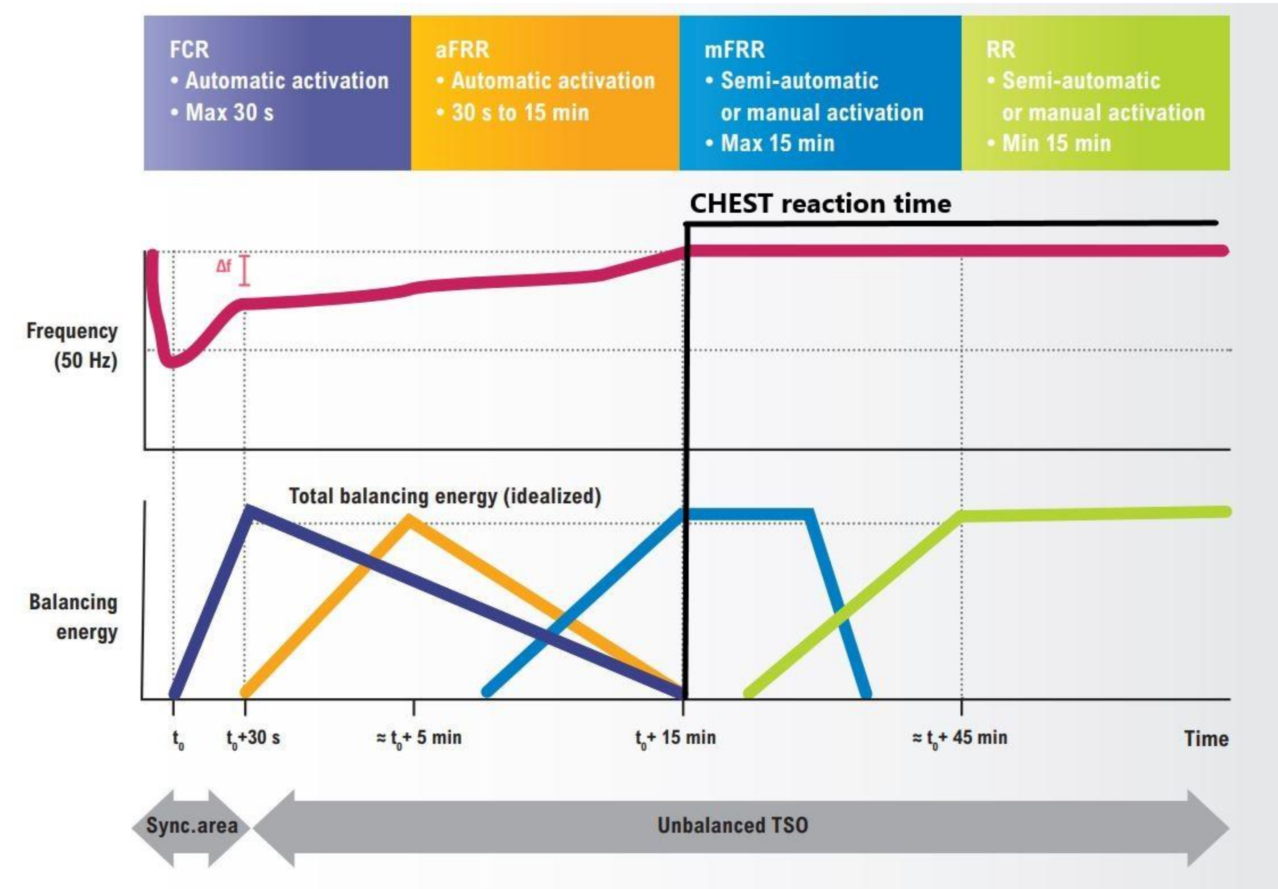

Figure 1 Balancing market process for frequency restoration [21]

The principles of these future balancing services are explained in Figure 2.

RESERVE POWER TYPE	DEFINITION	PURPOSE[1]
FCR	The active power reserves available to contain system frequency after the occurrence of an imbalance.	The frequency containment process stabilises the frequency after the disturbance at a steady-state value within the permissible maximum steady-state frequency deviation by a joint action of FCR within the whole synchronous area.
FRR (aFRR and mFRR)	The active power reserves available to restore system frequency to the set point value frequency and, for a synchronous area consisting of more than one load-frequency control area (LFC area), to restore power balance to the scheduled value.	The frequency restoration process controls the frequency towards its set point value by activation of FRR, and replaces the activated FCR. The frequency restoration process is triggered by the disturbed LFC area.
RR	The active power reserves available to restore or support the required level of FRR to be prepared for possible additional system imbalances, including generation reserves.	The reserve replacement process replaces the activated FRR and/or complements the FRR activation by activation of RR. The replacement reserve process is activated in the disturbed LFC area.
IN	A process agreed between TSOs that enables the avoidance of the simultaneous activation of aFRR in opposite directions, taking into account the respective frequency restoration control errors as well as the activated aFRR and correcting the input of the involved frequency restoration processes accordingly.	The imbalance netting process is designed to reduce the amount of simultaneous and counteracting aFRR activation of different participating and adjacent LFC areas via imbalance netting power exchange.

Figure 2 Definition and purpose of balancing processes [21]

In addition to the balancing services above, CHEST should be able to also participate in the intraday (t_0+ 3 hours) and day-ahead (t_0+ 1 day) markets as well as in long term agreements (e.g., for seasonal storage) as shown in Figure 3.

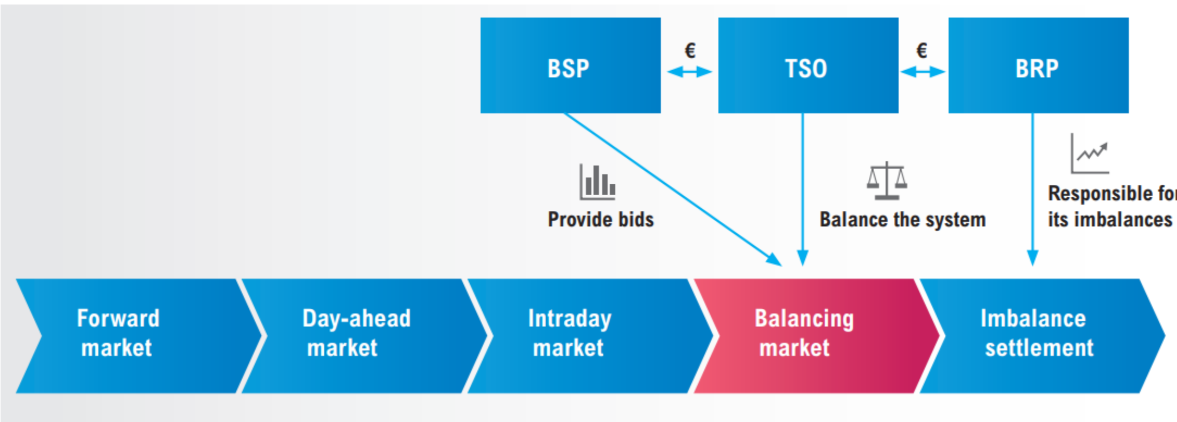

Figure 3 Balancing market sequence in electricity markets and its participants [21]

The scope of participation in the markets should be widened but also prioritized to those markets that allow the highest value to be accessed. The further away from a real time supply (t_0), the lower the value of the flexibility service provided. Hence mFRR and RR services are likely to be most attractive for participation.

2.2. Energy storage market

The CHEST system has different functionalities as it can both store electrical and thermal energy. It can thus compete with pure electric storage technologies. It has a wide potential, if not now so in the future, given reducing investment costs and increasing penetration of RES and changing market of consumers and prosumers.

As shown in Figure 4 it fits with the capacity range between 1 MW and 100 MW where there is not many competitors and demand for maintaining energy from inflexible RES is growing.

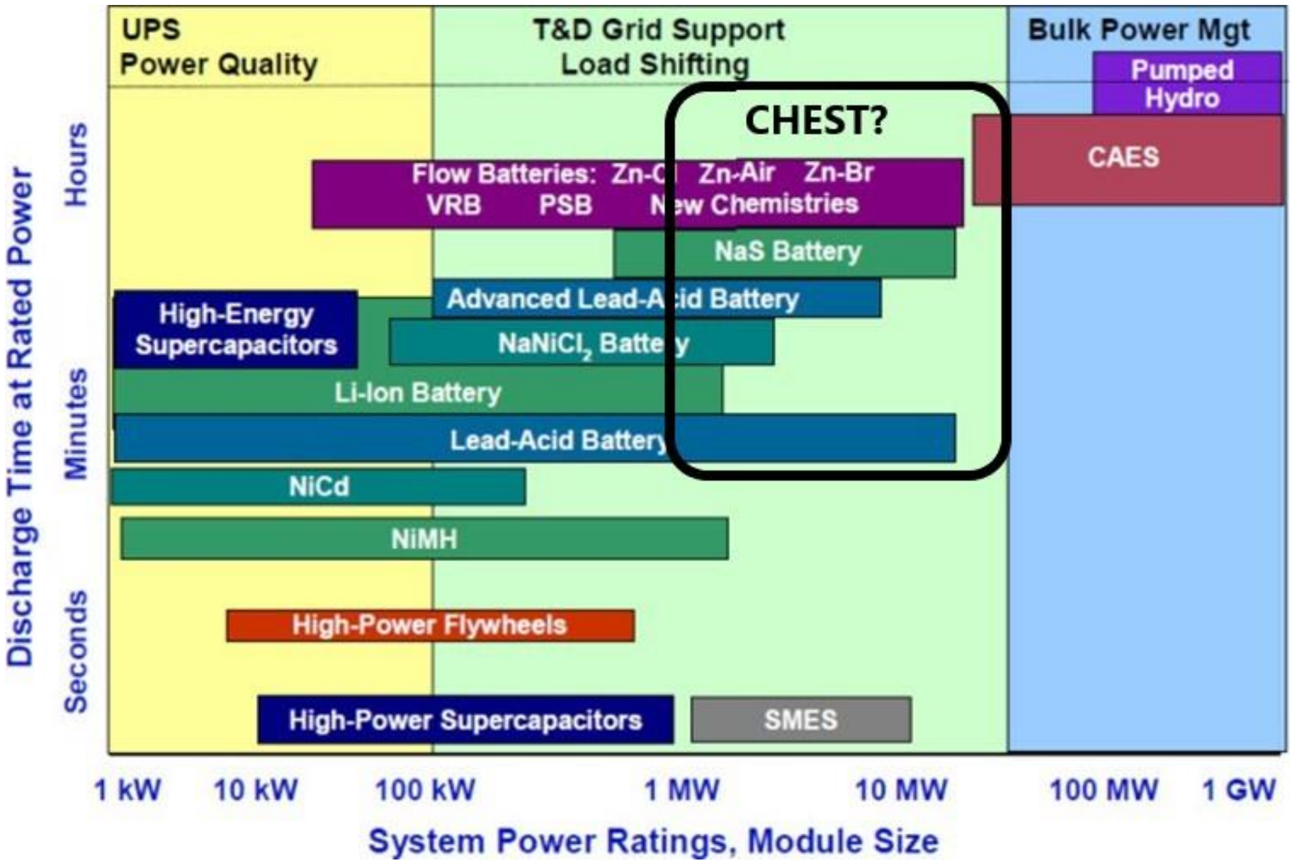

Figure 4: Overview of the storage range and discharge time for electric storage technologies PHES and potential allocation for the CHEST technology (2012)[5].

The investment unit costs for the key heat and electricity storage technologies are shown in Table 2.

For comparison the corresponding cost of power capital cost of operation and maintenance have been calculated for the aggregated CHEST system (HP + HTTES + ORC) and shown in Table 3.

Table 2: Cost comparison between different battery technologies for comparison with the CHEST solution [17], [18]

Technology name	Cost of Power capital	Cost of Energy capital	Cost of Operation and maintenance
Energy Storage technologies	(S/kW)	(S/kWh)	((S/kwh/kW/year)
SMES	200-489	1000-72000	0. 001-18 .5
FES	250-350	1000-14000	0. 004-20
PHS	2500-4300	5-100	0.004-3.0
TES	200-400	20-60	Not available
CAES	400-1000	2-120	0. 003-25
Batteries			
Lead Acid	300-600	200-400	-50
Li-ion	1200-4000	600-3800	Not available
NaS	350-3000	300-500	-80
Nicd	500-1500	800-2400	-20
VRB	600-1500	150-1000	-70
ZnBr	400-2500	150-1000	Not available
PSB	700-2500	150-1000	Not available
Capacitors	200-400	500-1000	0. 005-13 .0
Supercapacitors	100 450	300-2000	0.005 6.0

Table 3: CAPEX and OPEX of the combined *CHEST solution; calculated based on* [19].

	Cost of Power Capital March 2022 ($/kW)	Cost of Operation and maintenance March 2022 ($/kWh)	Cost of Power Capital future 20-30 years perspective ($/kW)	Cost of Operation and maintenance future 20-30 years perspective ($/kWh)
CHEST-system (March 2021)	17230	1.7	8700	1.7

These aggregated cost estimates for the CHEST technology are based on the latest (May 2022) investment and operation costs for each individual component which in both USD and originated estimations at EUR are collated in Table 4. Since the electricity is produced in the CHEST system as an effect of complex energy conversion (power to heat to power) using different production and energy storage units, specific efficiencies and other operation parameters have been assumed for each of them using the optimal range established in other deliverables which is as follows [16]:

1. The cost of power capital was established using following COPs and efficiencies and sizing relation between HP and ORC:
   - heat pump COP with nominal value for the calculated systems between 4.0 and 5.4., 4.0 used in the table;
   - ORC efficiency at level between 10% and 21%, 15% used in the table;

- ORC to HP capacity ratio which for the most efficient system performance was concluded at between 25%-50% (ORC up to four times smaller than HP), 25% used in the table.

2. The cost of energy capital depends on full load operation hours of HP and ORC and storage volume/duration which in previous deliverables [16] was identified as
   - HP and ORC units have been proved that they can operate simultaneously and operation time each of the plant between 4000 and 6000 hours/year.
   - The most cost-effective storage volume was between 6 and 12 hours of HP thermal capacity.

3. The cost of operation and maintenance per kWh of electricity produced is the combination of the unit O&M cost per 1 kWh_{el} of the ORC turbine, and 1kWh_{th} of corresponding heat stored in the HTTES and heat produced in HTHP required for achieving this electrical effect from the system.

Table 4: CAPEX and OPEX of the *CHEST solution per component [19].*

	Units	prices March 2022	prices future 20-30 years perspective	Units	prices March 2022	prices future 20-30 years perspective
CAPEX	HP EUR/kW_{th}	350	250	HP USD/kW_{th}	372	266
	ORC EUR/kW_{el}	1000	850	ORC USD/kW_{el}	1064	904
	HTTES (latent + sensible) EUR/kWh	100 (LTES) + 3 (STES)	50 (LTES) + 3 (STES)	HTTES (latent + sensible) USD/kWh	106 (LTES) + 3.2 (STES)	53 (LTES) + 3.2 (STES)
OPEX	HP EUR/MWh_{el}	5	5	HP USD/MWh_{el}	5.3	5.3
	ORC EUR/MWh_{el}	10	10	ORC USD/MWh_{el}	10.6	10.6
	HTTES (latent + sensible) EUR/MWh_{th}	5 (both LTES and STES)	5 (both LTES and STES)	HTTES (latent + sensible) USD/MWh_{th}	5.3 (both LTES and STES)	5.3 (both LTES and STES)

From the economical point of view CHEST has currently significantly higher costs than other technologies. The cost of the CHEST plant is expected to gradually reduce over the years as the HP and ORC components should get integrated and cost of the latent storage built of PCM materials will potentially halve. Moreover, the CHEST system has advantages over other storage technologies from the technical point of view such as:

- Is more compact for the same electric capacity,
- has more stable operation over time (does not loose efficiency over years),
- has functionality of both thermal and electric storage,
- does not depend on geographical features,
- can be used as seasonal storage.

3. Business models

3.1. CHEST as a provider of aggregated services in a minigrid

The main goal of the business models analysis is to study several business cases involving the CHEST system. The first business case involves an industrial park in Denmark, called GreenLab Skive (or GLAS), where several industries have waste heat and/or heat needs (see Figure 5 for an overview of the park).

Figure 5. 3D aerial view of current and future industries implanted in GLAS [6]

The different companies from the industrial sector of GLAS could rely on the nearby district heating network for their heat supply (see Figure 6), depending on the temperature level of their heating needs (if they are low enough). They would need to connect to it by implementing a local extension of the network. The industrial companies on the GLAS site with waste heat currently need to use dry coolers to get rid of it. In this context, the implementation of CHEST could be an alternative that would enable the exchange of heat between the different actors while producing electricity.

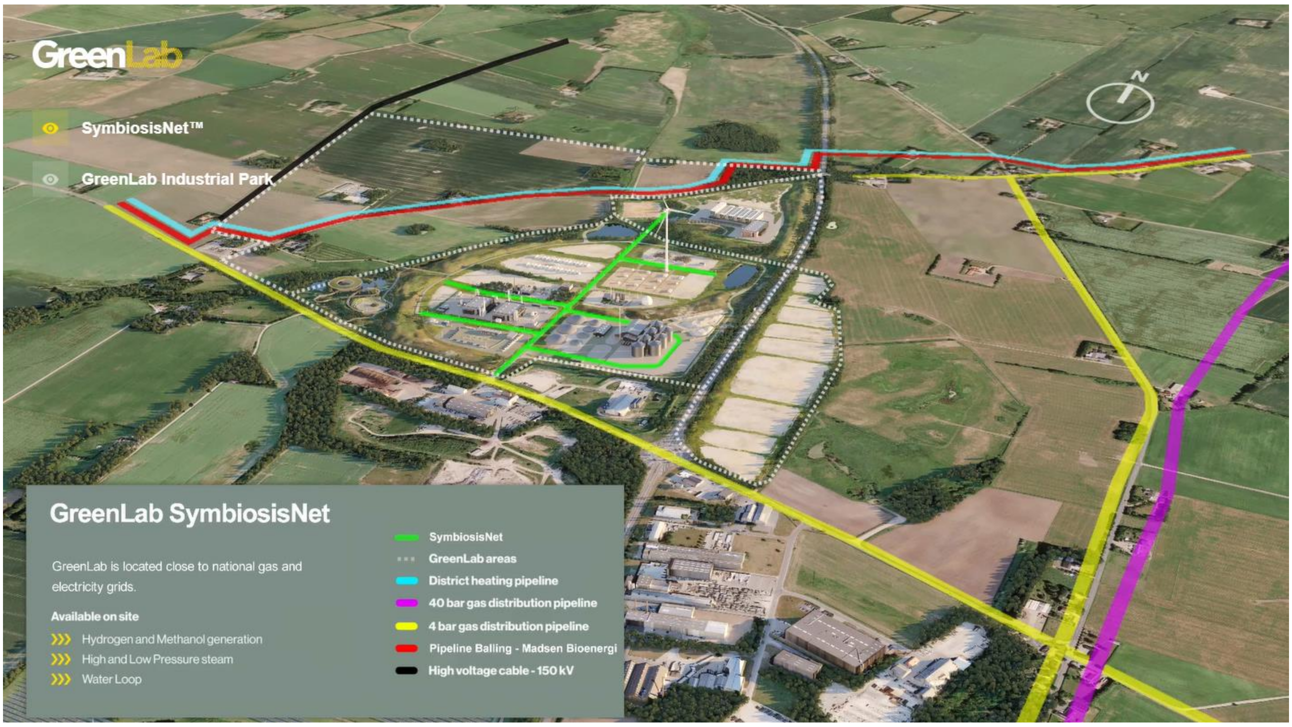

Figure 6. 3D aerial view of the industrial site of GLAS and the surrounding energy grids

To be able to transfer extra heat between the different industries, the sensible heat storage of the CHEST system, which is used for heat transfer at the core of the process, would be replaced by respectively a heat source and a heat demand/sink (see Figure 7 and Figure 8). In practice this means that the heat delivered at the subcooler of the heat pump would be sent directly to an industrial company on site (through the forward pipe of the local implemented district heating line), and the heat delivered to the preheater in the ORC cycle/loop would be provided by industrial waste heat available on the GLAS site and sent to the CHEST system through the local implemented district heating line.

For the current business case, the temperature levels and the timing of these heat exchanges aren't studied in detail. It is assumed that both cycles (heat pump/charge of the system, and ORC/discharge of the system) occur for a given number of hours per year. This number of operating hours is provided in Table 5.

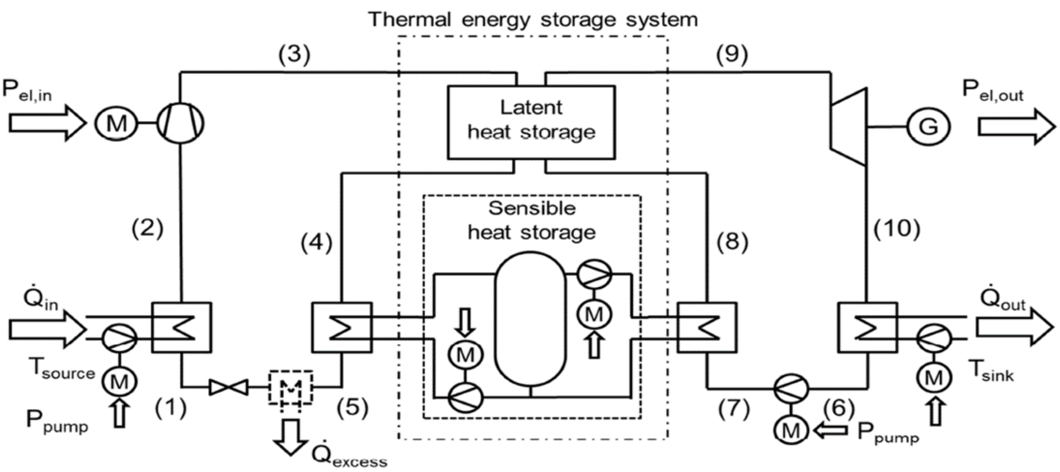

Figure 7: Schematic of the CHEST system

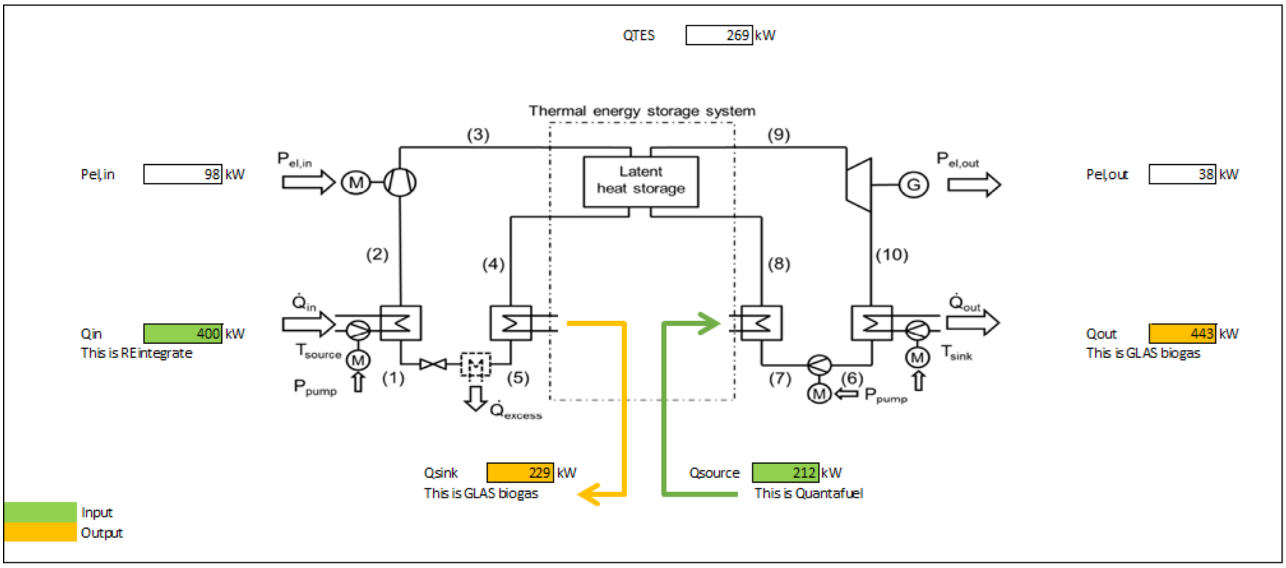

Figure 8: Schematic of the CHEST system variation used for the business case in GLAS

Data from GLAS was retrieved (see Figure 9) and used to identify the possibility of using the CHEST system as an alternative to extending a local district heating network or creating a new one (see below for details of the reference scenario that the CHEST scenario will be compared with).

3.1.1. Techno-economic data and assumptions

The main techno-economic assumptions used as a starting point are summarized in the following Table 5:

Table 5: General techno-economic assumptions for the CHEST system

General techno-economic assumptions		
System lifetime	30 [7]	years
Electricity price - purchase	65,2[b]	€/MWh
Electricity price - sell	65,2	€/MWh
Number of operating hours	5600[c]	hours/years
Heat cost - purchase	40	€/MWh
Heat cost - waste	0	€/MWh
Tax applied on “regular” electricity	119 [9]	€/MWh
Tax applied on electricity used to produce heat[d]	0,537	€/MWh

In this section, the main techno-economic assumptions of the CHEST system are presented. Then the same is done for the reference scenario. For both systems, investment costs and operational costs are given.

[b] Based on report from IEA of 2021 [8], stating an electricity price for the industry of 77,1 $/MWh in Denmark, which translates to 65,2 €/MWh with an average exchange rate of 0,8458 €/$ in 2021

[c] Data from GLAS, see Figure 9. This number is the total number of charging and discharging hours

[d] 0,537 €/MWh (4 DKK/MWh) is the tax applied in Denmark in 2020 for electricity [9] that is being used for heat production (power to heat), instead of the 119 €/MWh, which is the tax for regular use of electricity (884 DKKK/MWh)

Technical data from GLAS

The technical data retrieved from GLAS is presented in Figure 9. From this table, the data from the different heat sources/sinks will be used to make an energy balance, and the temperature levels will be assumed to be appropriate for the CHEST system, as the main purpose of this study is to analyze economic feasibility/business models and not technical feasibility. The same goes for the temporality of the CHEST system operations: the heat exchanges are assumed to be available at any time, during the total assumed operating hours of the system (5600 hours).

Company	Energy process	Excess electricity capacity kW	Excess heat capacity kW	Heating need kW		T required °C	T excess °C	Medium	Operation hours/year	Note
GLS										
	Cooling transfomers									Transformers have typical 2% heatloss to recover
Quantafuel									?	Plastic to oil process – pyrolysis
			260			160	120	Termal oil		
			600			115	80	Termal oil		
GreenLab Skive Biogas									8760	
	Biogas upgrading			5700		127	132	Termal oil		
	Excess heat		?			?	?			Remaining excess heat
Danish Marine Protein									?	
	Drying			1600		250-300		Air		
	Excess heat		?			?	?			
Green Hydrogen										Electrolysis
	Excess heat		?			?	?			
REintegrate/GLAS P2X									5600	Methanol production
	Steam demand			600		150			?	
	Excess heat		400			?	70		?	
Everfuel										H2 storage, tankloading
	Excess heat		?			?	?			
Nomi										Waste treatment
	Excess heat		?			?	?			
Wind farm and PV		80000								

Figure 9: Data retrieved from the industrial campus at GLAS

The studied variation of the CHEST system is made of three main components: the Heat Pump (HP), the Organic Rankine Cycle (ORC) and the Latent Thermal Energy Storage (LTES). To support the operation of these three components, District Heating (DH) pipes connect the CHEST system to the different industrial actors located on the GLAS site, with either a heat demand or waste heat available (see Figure 13).

Each component is individually analyzed in the following sections, starting from the main assumptions, moving into the calculation, and finally analyzing the main resulting costs.

Heat pump (HP)

The main techno-economic assumptions for the heat pump of the CHEST system are summarized in the following Table 6, and are mostly based on CHESTER deliverables as well as Danish experience with large scale heat pumps[5]:

Table 6: Heat pump techno-economic assumptions

HP assumptions		
Input heat at evaporator ”Qevap”	400[c]	kW
COP of the HP	5,1 [7]	-
HP Investment cost - kW_{th}	500[6]	€/kW_{th}
Fixed O&M HP (excluding electricity)	2000 [12]	€/MW_{th}/year
Variable O&M HP (excluding electricity) - MWh_e	5 [6]	€/MWh_e
LHR (Latent heat ratio)	0,54 [7]	-

The heat pump which was chosen from [7] is a Butene heat pump, since it gives the best thermodynamic performance under the temperature level of the waste heat source (70 °C). The heat pump is highlighted in Figure 10.

[5] By large scale, several hundreds of kilowatts of heating or cooling power is meant

[6] The CHESTER consortium [10] has established specific investment costs of 350€/kW_{th} heating capacity for the heat pump, and O&M costs of 5 €/MWh_{el} consumed, but here the assumption from [11] was used instead, because it corresponds better to the investment of a small-scale heat pump, while the O&M cost was kept

Heat source temperature	PCM material	Melting point	Refrigerant	Coefficient of performance (COP)	Latent-sensitive heat ratio (RLS)	PCM melting enthalpy	PCM density (roPCM)	Condensing temperature (condTemp)	ORC efficiency (effORC)	Power ratio HP/ORC (power Ratio)
$40 \leq T < 55$	$LiNO_3$-$NaNO_3$-KNO_3	123 ºC	Butene	3.2	0.54	140 kJ/kg	2068 kg/m^3	55 ºC	0.079	2.566
$55 \leq T < 70$	$LiNO_3$-$NaNO_3$-KNO_3	123 ºC	Butene	4	0.54	140 kJ/kg	2068 kg/m^3	55 ºC	0.079	2.566
$70 \leq T < 80$	$LiNO_3$-$NaNO_3$-KNO_3	123 ºC	Butene	5.1	0.54	140 kJ/kg	2068 kg/m^3	55 ºC	0.079	2.566
$80 \leq T < 85$	$LiNO_3$-KNO_3	133 ºC	R1233zd (E)	5.7	0.58	150 kJ/kg	2018 kg/m^3	70 ºC	0.097	2.5
$85 \leq T < 95$	KNO_3-$NaNO_3$-$NaNO_2$	142 ºC	R1233zd (E)	5.9	0.55	110 kJ/kg	2006 kg/m^3	80 ºC	0.09	2.5

Figure 10. Refrigerant chosen from the list of possible refrigerants proposed in Chester deliverable D6.5 (circled in blue)

Organic Rankine cycle (ORC)

The main techno-economic assumptions for the ORC are presented in Table 7:

Table 7: ORC techno-economic assumptions

ORC assumptions		
Power ratio HP/ORC	2,57 [7]	-
Efficiency of ORC	7,9% [7]	-
Investment cost ORC	1000 [10]	€/kW_e
Fixed O&M cost	0	€/MW_e/year
Variable O&M ORC	10 [12]	€/MWh_e

Latent thermal energy storage (LTES)

The main techno-economic assumptions for the LTES are presented in Table 8:

Table 8: LTES techno-economic assumptions

LTES assumptions		
Investment costs LTES	100 [10]	€/kWh_{th}
Fixed O&M LTES	0	€/MWh
Variable O&M LTES	5 [10]	€/MWh_{th}
Sizing of LTES	24 [13]	hours of storage

DH pipes

The last elements to be included in the calculations for the CHEST system of this business case are the DH pipes. The required length of the pipes was estimated by connecting the involved industrial companies with district heating pipes on QGIS (see Figure 13). General techno-economic assumptions based on Danish experience are used, as presented in Table 9:

Table 9: DH pipes techno-economic assumptions

DH pipes assumptions		
Diameter of DH pipes	DN100	
Cost of pipes	403[7]	€/m
Max. heat rate delivered	0,600	MW

3.1.2. Economic scenarios and financial parameters

Most financial parameters are presented in the previous section. They correspond to the starting case scenario for the CHEST system, and the sensitivity analysis (presented below) will study the influence of varying several techno-economic parameters on the economy of the scenario. For all technologies, both investment costs and operational costs are considered.

Reference scenario and comparison methodology

Regarding the reference configuration to which the CHEST scenario will be compared, it relies on two main assumptions:

- The heat demands that are sourced from the CHEST system are instead supplied by district heating (which would need to be implemented on the GLAS site)[8]
- The waste heat produced by the industrial companies on site which would be exchanged through the CHEST system is dissipated by means of dry coolers, at the expense of the industrial companies

[7] Including civil work and installation, for twin pipes, based on Danish experience. Corresponds to 3000 DKK/m

[8] This wouldn't be possible in practice, as some of the temperatures required by the industrials are too high to be reached with a standard district heating network (required temperatures reported in Figure 9 range from 115°C to 300°C), but it gives a decent reference point for a (very) competitive heating solution, with some investment costs and stable operational costs (heat purchase). This will facilitate the sensitivity analysis

The reference and CHEST scenarios are schematized in Figure 11.

For the comparison between the reference scenario and the CHEST scenario alternative, the following methodology will be used:

- Investment costs are calculated for each industrial company in the reference case (district heating pipes for the industries with a heat demand, dry air coolers for the industries with waste heat, see details below)
- Yearly operational costs are calculated for each industrial company in the reference case (costs associated with the yearly energy needs of the industries, see details below in Sections 3.1.2 and 3.1.3)
- Then the reference scenario (accumulated) expenses are calculated over 30 years for each industrial company involved. It is assumed that all investment costs are made at year 0 of the analysis, and the accumulated expenses increase every year with the yearly costs for each industrial
- Then the same is done for the CHEST system alternative: the investment costs and the yearly operational costs are calculated for the entire CHEST system
- Then the CHEST scenario (accumulated) expenses are calculated over 30 years for each industrial company involved. The investment costs are assigned to year 0 again, and shared between the industries, proportionally to their share of year 0 expenses in the reference scenario[9]. For the following years, the same principle is applied, the industries share the yearly operational costs (and revenues) of the CHEST system, proportionally to their share of the given year in the reference scenario[10]
- The accumulated expenses of each industry over the 30 years in the two scenarios are then compared
- It is expected that the CHEST alternative system will require higher investments and lower yearly operational costs, so the accumulated expenses of the reference scenario should at some point surpass the accumulated expenses of the CHEST scenario. For each industrial partner, the following economic KPIs were determined:
    - The tipping point in time where the CHEST scenario has generated economic savings (return on investment year) compared with the reference scenario
    - The total economic savings at year 30, if any (negative value if the balance is negative)
    - The ratio between economic savings for the CHEST scenario and the total expenses of the reference scenario at year 30

[9] Example: assuming two industrials are involved in the CHEST heat exchange system, and the first one invests 300 k€ in the reference scenario at year 0, while the second industrial invests 100 k€. The total expenses at year 0 in the reference scenario are then 400 k€, the first industrial's share is 75 %, and the second, 25 %. If the corresponding CHEST system alternative requires an investment of 1 M€, then the first industrial would cover 750 k€ and the second, 250 k€. This logic does not include the district heating pipes investment, which are mostly supported by the industrial with a heat demand (see components sizing calculations for more details on this point)

[10] Example: assuming two industrials are involved in the CHEST heat exchange system, and the first one has a 30 k€ in the reference scenario at year 5, while the second industrial has an expense of 10 k€. The total expenses at year 5 in the reference scenario are then 10+30=40 k€. The first industrial's share is 75%, and the second, 25%. If the corresponding CHEST system alternative has operational costs of 10 k€ at year 5, then the first industrial would cover 7,5 k€ and the second, 2,5 k€. Same principle goes with the share of the revenues

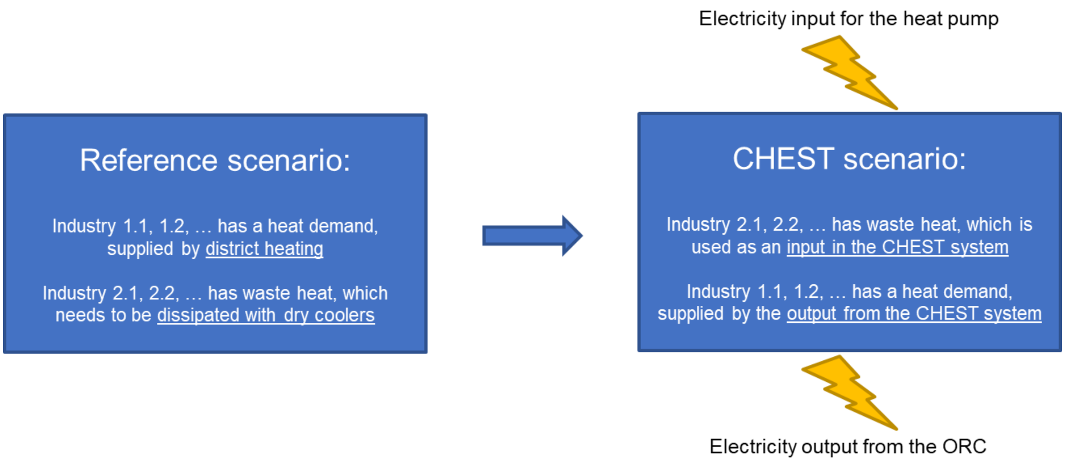

Figure 11. Diagram presenting the reference scenario (left side of the figure) and the CHEST alternative (right side of the figure)

The results of the CHEST system sizing calculations provide the energy balance obtained in Figure 8 (see next section for the calculations methodology), and Table 10 presents the corresponding reference scenario. The techno-economic assumptions for the reference scenario are presented in the following sub-sections.

Table 10. Summary of CHEST system heat balance calculations and the corresponding reference scenario

CHEST scenario			Reference scenario		
			Industries with a heat demand		
Heat output from HP subcooler	229	kW	Heat demand from GreenLab Skive biogas (GLAS biogas) covered in the ref. scenario	671	kW
Heat output from ORC condenser	443	kW			
			Industries with waste heat		
Heat input to HP evaporator	400	kW	Waste heat from REintegrate (MeOH prod.)	400	kW
Heat input to ORC preheater	212	kW	Waste heat from Quantafuel (Pyrolysis)	212	kW

District heating costs of the reference scenario

In this business case we assume for the reference scenario that district heating costs consist of investment costs (DH pipes and a fee to connect to the DH network) and operational costs (a fixed price for heat purchase). The DH pipes investment is calculated based on the distance from the industry using heat to the local DH network (see Figure 13). The connection fee is assumed to be 1050 DKK/kW (based on Danish standards), which corresponds to 140,94 €/kW (assuming a constant exchange rate of 7,45 DKK/€).

In the reference case, the DH network investment costs should be shared between the industries involved in the heat exchange, proportionally to their required heating capacity[11]. In our business case, only one industry has a heat demand. This industry thus covers the entire district heating pipes' investment costs.

[11] Example: industrials 1 and 2 have a heat demand of respectively 100 kW and 300 kW. If the DH pipes investment costs are 100 k€, then industrial 1 would cover 25 k€, and industrial 2 would cover 75 k€. The connection fee for industrial 1 would be 100*140,94=14094€ and 300*140,94=42282€ for industrial 2

Waste heat dissipation costs of the reference scenario

In the reference scenario, dry coolers are used for each waste heat stream dissipation. The associated costs consist of investment costs (investment in the dry coolers) and operational costs (electricity for the dry coolers), which are calculated with the assumptions from Table 11.

Table 11: Dry cooler techno-economic assumptions

Dry coolers assumptions		
Efficiency	80%[12]	
Investment cost	60[13]	€/$kW_{th,capacity}$
Ratio electricity/heat	45 [15]	kWh_{el}/MWh_{th}
Lifetime	15[14]	years
Fixed O&M costs	0	€/MWh

3.1.3. Sizing calculations of the CHEST and reference scenarios' components

Heat pump

The heat load at the evaporator is the starting point for the calculation process (see Figure 12). It is set based on the data from GLAS for REintegrate, which has an excess heat power available of 400 kW. It is assumed that this excess heat is available at any time of the day, 5600 hours a year.

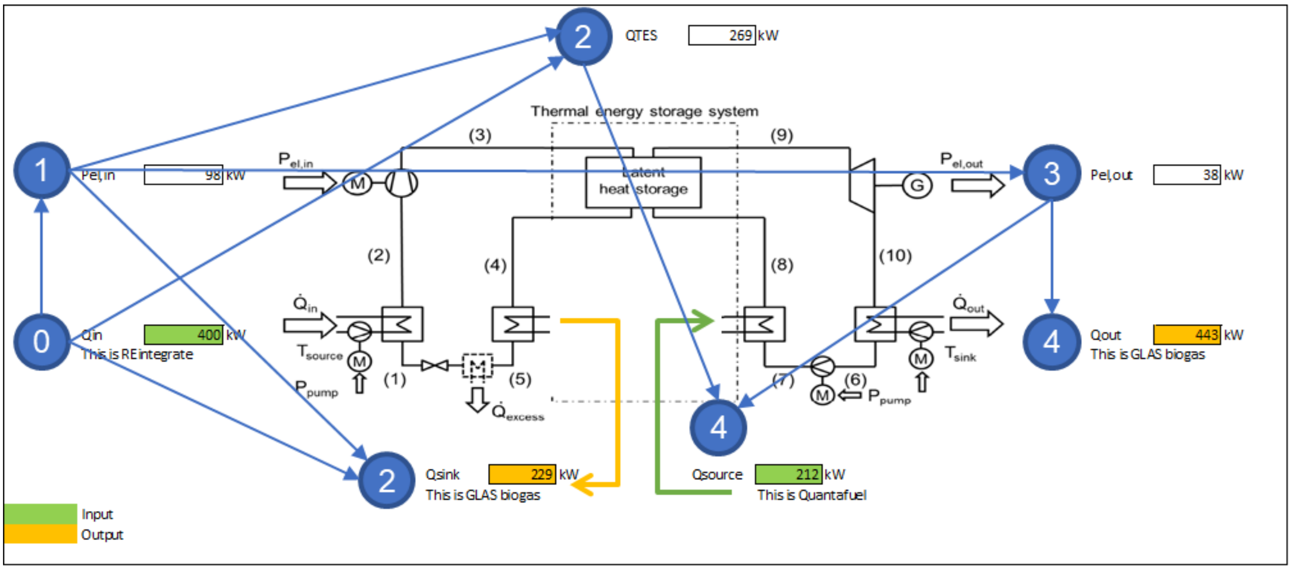

Figure 12. Component sizing process illustrated: first the thermal power at the evaporator of the HP is set (0), then the electrical power of the HP is determined (1). Then the heat stored into the LHS (2) and delivered to the subcooler of the HP of the CHEST system is calculated (2). From there, the power output of the ORC is determined (3), and to finish the heat required at the ORC cycle pre-heater (4) and the heat delivered at the condenser of the ORC are calculated (4)

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[12] Slight overestimation of the dry air cooler capacity to have a margin for actual operations
[13] Based on Danish experience with dry air coolers
[14] For simplification reasons of the economic analysis, the investment for the dry coolers is assumed to be made twice, at year 0, to cover 30 years of lifetime for the dry coolers

Based on this input, the system is evaluated, and the appropriate COP of 5,1 is chosen based on the typical performances of a heat pump with similar size (see [11]), considering a subcooler (sensible heat storage between the heat pump and the PCM storage). This data is provided in Chester deliverable 6.5.

Starting from these two main parameters, the electric input to the heat pump is calculated:

$$P_{el,HP} = \frac{Q_{evap}}{COP - 1} = \frac{400\ kW}{5{,}1 - 1} = 98\ kW$$

The heat at the condenser (LHS and subcooler) is then calculated as (assuming no heat losses):

$$Q_{cond} = Q_{evap} + P_{el,HP} = 400\ kW + 98\ kW = 498\ kW$$

By using the number of operating hours per year, the total heat production over a year is calculated, as well the heat drawn from REintegrate and the electricity required to power the system.

Part of the heat produced is delivered to GLAS biogas, part of it is instead sent to the latent heat storage according to the latent heat ratio (LHR) (see Figure 8).

Results

By using the results of the calculation that has been performed, the economy of such a system is evaluated, using the economic parameters as stated in Table 6. The key parameters are included in Table 12:

Table 12: Heat pump calculation results

Sizing of system		
Nominal electric capacity of HP	97,6	kW
Total heat power output of HP	498	kW
Heating power delivered to LTES	269	kW
Heating power delivered at the HP subcooler	229	kW
Energy (5600 operating hours per year)		
Heat input from REintegrate	2240	MWh/year
Electricity consumption by HP	546	MWh/year
Heat production by HP	2786	MWh/year
Heat delivered to LTES	1505	MWh/year
Heat delivered to GLAS biogas	1282	MWh/year
Costs		
CAPEX HP	249	k€
Fixed O&M (excluding electricity)	1,0	k€/year
Electricity costs HP	35,9	k€/year
Variable O&M HP (excluding electricity)	2,7	k€/year

ORC

The power ratio HP/ORC is an output from Chester deliverable 6.2, therefore a direct link between the electricity input of the HP and the ORC is established, which gives an ORC electric power of 38 kW. Once the power input of the ORC is calculated, the sizes of the other components of the ORC are calculated using the ORC efficiency.

The operating hours of all the components of the system (including the ORC) are assumed equal to the operating hours of the heat pumps (5600 hours). This does not mean that the components work simultaneously during the entire year, but that there are at least some hours of simultaneous operations during the year (since 5600 hours is higher than 4380 hours, which is half of 8760 hours in one year). Using this parameter, the heat delivered to Quantafuel over a year is calculated.

Once the main sizing of the system components is completed, the economic figures of the system are also calculated based on the assumptions from Table 7.

Results

The results are presented in Table 13:

Table 13: ORC calculation results

Sizing of the system		
ORC electrical power output	38,0	kW
Heating power required by ORC	481	kW
Heating power required for the ORC pre-heater	212	kW
Heating power delivered at the ORC condenser	443	kW
Energy (5600 operating hours per year)		
Electricity production from ORC	213	MWh/year
Heat delivered to GLAS biogas	2478	MWh/year
Heat input from Quantafuel	1186	MWh/year
Costs		
CAPEX ORC	38,0	k€
Variable O&M	2,1	k€/year
Revenue from electricity sales	13,9	k€/year

LTES

The main assumption considered for the LTES dimensioning is that the storage should be able to store 24 hours of charging of the system at the rate set by the HP. For the yearly stored energy/heat in the LTES, once again the assumption is that the power delivered to the LTES (269 kW) is summed over 5600 hours. By using the economic figures included in Deliverable 6.2, the economy of such a system is also calculated.

Results

The main results for the LTES system are included in the following Table:

Table 14: LTES calculation results

Sizing of the system		
Size of LTES (capacity)	6,45	MWh
Energy (5600 operating hours per year)		
Energy stored in the LTES	1505	MWh/year
Costs		
CAPEX LTES	580	k€
Variable O&M	8	€/year

DH pipes

The necessary pipe length to connect the different industries was estimated using the program QGIS (see Figure 13 and Table 15 for the results), and the share of associated pipe investment is distributed in the following way:

- The pipe connecting GreenLab Skive biogas to the local district heating network is 788 meters long. This constitutes the main district heating line of both the reference scenario and the CHEST alternative scenario[15]. Associated investment costs are covered in both scenarios by GLAS biogas
- The length of the pipe connecting Quantafuel to this main district heating line is 81 m
- The length of the pipe connecting REintegrate to this main district heating line is 117 m
- The investment costs of the pipes connecting Quantafuel and REintegrate to the main district heating line are shared between the different industries, proportionally to their share of the total investment costs in the reference scenario

The reason for this distribution of the DH pipes investment costs is that Quantafuel and REintegrate should not have to invest in the infrastructure that enables GLAS biogas to be supplied with heat, but only the part of the network that enables them to connect to the CHEST system which helps them get rid of their waste heat.

Based on the calculated pipe lengths and parameters from Table 9, the results presented in Table 15 are obtained.

[15] In the CHEST scenario, the DH pipeline length is overstimated, but this could account for the connection costs (heat exchangers) between the CHEST system and the main district heating pipeline

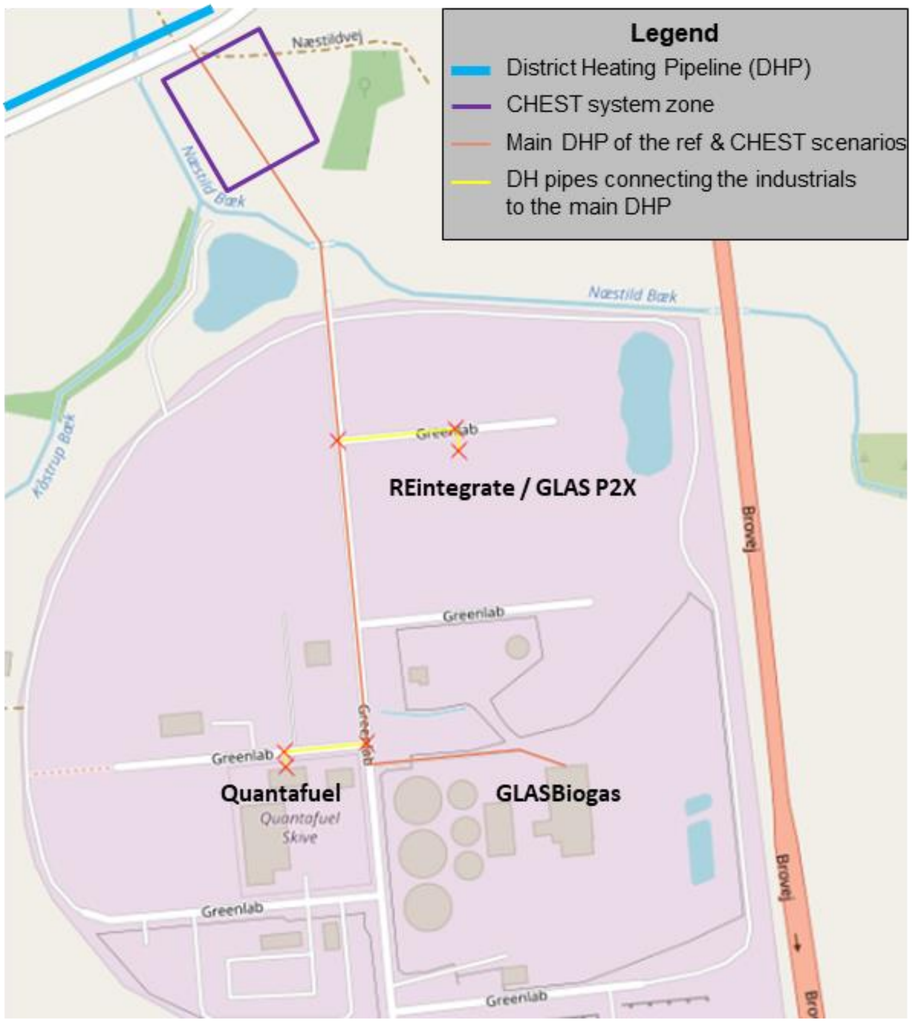

Figure 13. Map of the GLAS campus and drawing of the district heating pipes necessary to connect the different industrial companies (yellow lines and orange crosses) to the main district heating line of the reference and CHEST scenarios (orange line), the area of the CHEST system and the local district heating pipeline

Table 15: DH pipes calculation results

DH pipes length and associated investment costs		
Length of DH pipes to GLAS biogas, CHEST	788	m
Investment cost of DH pipes of GLAS biogas	317	k€
Length of DH pipes to Quantafuel, CHEST	81	m
Length of DH pipes to REintegrate, CHEST	117	m
Length of DH pipes connecting the waste heat producers to the main district heating line of CHEST	198	m
Investment cost of DH pipes connecting waste heat producers to the CHEST system	79,7	k€
Variable O&M	0	€/year

Reference scenario

The heat output streams provided by the CHEST system in the CHEST scenario are 229 kW (HP) and 443 kW (ORC), a total of 671 kW. The heat input streams required are 400 kW (HP) and 212 kW (ORC). GLAS biogas has a total heat demand of 5700 kW, of which 671 kW will be considered covered, while REintegrate and Quantafuel have respectively waste heat streams of 400 kW and 260 kW, of which 400 kW and 212 kW will be considered used. Table 10 presents the corresponding heat demand and waste heat streams in the reference scenario. The main components that need to be considered for this scenario are the DH network and the dry coolers.

For GLAS biogas, the previous section already presented the DH pipes investment costs (the required pipe length is assumed equal in both scenarios), to which needs to be added the district heating subscription fee. Finally, the heat demand is provided at a given fixed price according to Table 5, and the economic results for GLAS biogas are presented in Table 16.

Table 16. Reference scenario calculations results for GLAS biogas

Sizing of the system		
Heating power delivered to GLAS biogas	671	kW
Energy		
Heat delivered to GLAS biogas	3760	MWh/year
Costs		
DH pipes investment	317	k€
DH power subscription fee	94,6	k€
Heat purchase costs	150	k€/year

For REintegrate and Quantafuel, in the reference scenario, the only costs are the ones associated with the dry coolers, and the economic results are presented in Table 17. For the electricity needs and the dry cooler capacity calculations, the parameters from Table 11 are used.

Table 17. Reference scenario calculations results for REintegrate and Quantafuel

Sizing of the system		
Waste heat from REintegrate	400	kW
Dry cooler capacity[16] for REintegrate	500	kW
Waste heat from Quantafuel	212	kW
Dry cooler capacity[16] for Quantafuel	265	kW
Energy		
Annual required electricity by REintegrate	101	MWh/year
Annual required electricity by Quantafuel	53,4	MWh/year
Costs		
REintegrate dry cooler investment	60,0	k€
Quantafuel dry cooler investment	31,8	k€
REintegrate annual costs (electricity purchase)	18,5	k€
Quantafuel annual costs (electricity purchase)	9,8	k€

3.1.4. Economic results

To summarize the previous sizing calculations, Table 18 presents the costs of the reference and CHEST scenarios. As presented in the previous sections, investment and annual costs for the CHEST system are shared between the different industrial companies proportionally to their expenses in the reference scenario, with the exception of the district heating pipes investment, which are distributed in a specific way (see previous section for details).

[16] Assuming an efficiency of 80%, according to Table 11

Table 18. Summary of the reference and CHEST scenarios calculations results

Reference scenario				**CHEST scenario**		
Investment costs (year 0)			**Share of total in reference scenario**	**Investment costs (year 0)**		
Total[17]	504	k€		Total CHEST system investment costs (without DH pipes)	932	k€
GLAS biogas	412	k€	81,8%	DH network pipe investment[18]	383	k€
				GLAS biogas total[19]	1144	k€
REintegrate	60,0	k€	11,9%	DH network pipe investment[20]	9,5	k€
				REintegrate total	120	k€
Quantafuel	31,8	k€	6,3%	DH network pipe investment[21]	5,0	k€
				Quantafuel total	63,8	k€
Annual costs (years 1 to 30)				**Annual costs (years 1 to 30)**		
Total	189	k€		Total CHEST annual costs (including deducted revenues from ORC electricity sales)	35,5	k€
GLAS biogas	150	k€	84,1%	GLAS biogas	29,8	k€
REintegrate	18,5	k€	10,4%	REintegrate	3,7	k€
Quantafuel	9,8	k€	5,5%	Quantafuel	1,9	k€

Based on these investment and annual costs, it is possible to determine the economic KPIs of this business case, using the assumptions presented in Table 5 to Table 11. These KPIs are presented in Table 19. Figure 14 to Figure 16 present the development of the expenses for GLAS biogas, REintegrate and Quantafuel, in both the reference and CHEST scenarios, together with the savings generated by the CHEST scenario compared with the reference scenario over 30 years.

Table 19. Economic KPIs for the industrial companies of the initial business case (with assumptions from Table 5 to Table 11)

Industrial company / **KPI [unit]**	**GLAS biogas**	**REintegrate**	**Quantafuel**
ROI compared to reference [year]	6,1	4,1	4,1
Total savings at year 30 [k€]	2885	385	204
Savings over expenses[22] ratio at year 30 [-]	141%	167%	167%

[17] In the reference case, the total investment required for the industrial companies is 317,3+94,6+60+31,8=504 k€, see Table 16 and Table 17

[18] Cost of the main district heating line, 788 meters of DN100, 317 k€ + share of the 198 meters of DN100 connecting the other industrials to the CHEST system, 0,818*79,7=65,2 k€

[19] 383 k€ + share of the CHEST system investment costs (without DH pipes), 0,818*932=762 k€

[20] 0,119*79,7=9,5 k€

[21] 0,063*79,7=5,0 k€

[22] Expenses at year 30 in the reference scenario, and savings at year 30 in the CHEST scenario

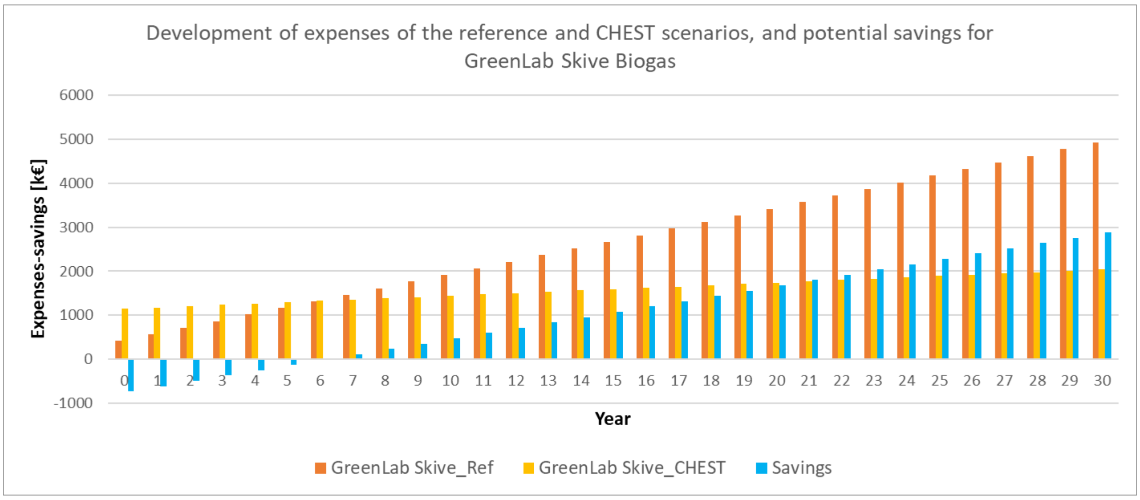

Figure 14. Development of the accumulated expenses for GLAS biogas in the reference (orange bars) and CHEST (yellow bars) scenarios, and potential savings (light blue bars) over 30 years

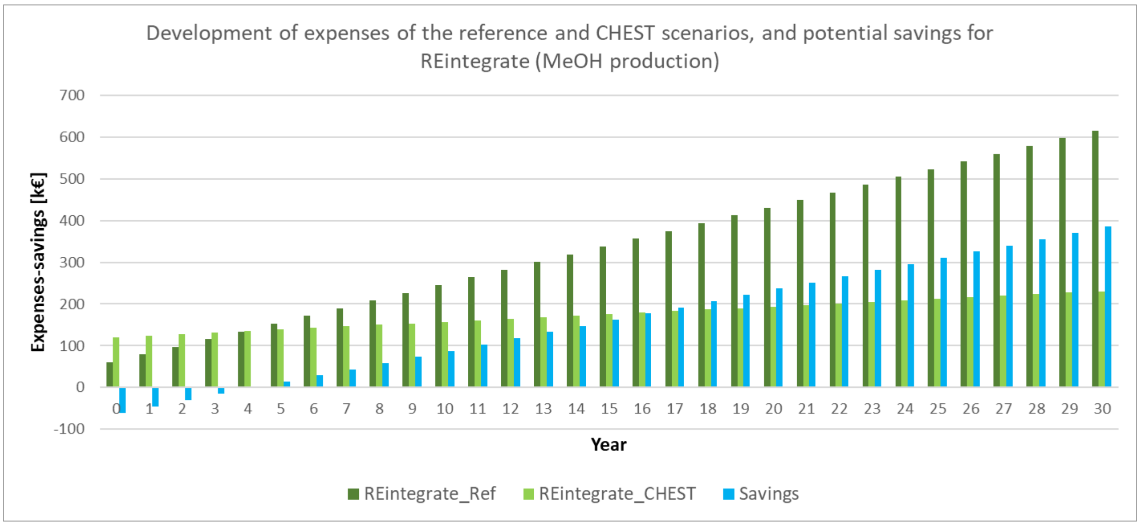

Figure 15. Development of the accumulated expenses for REintegrate in the reference (dark green bars) and CHEST (light green bars) scenarios, and potential savings (light blue bars) over 30 years

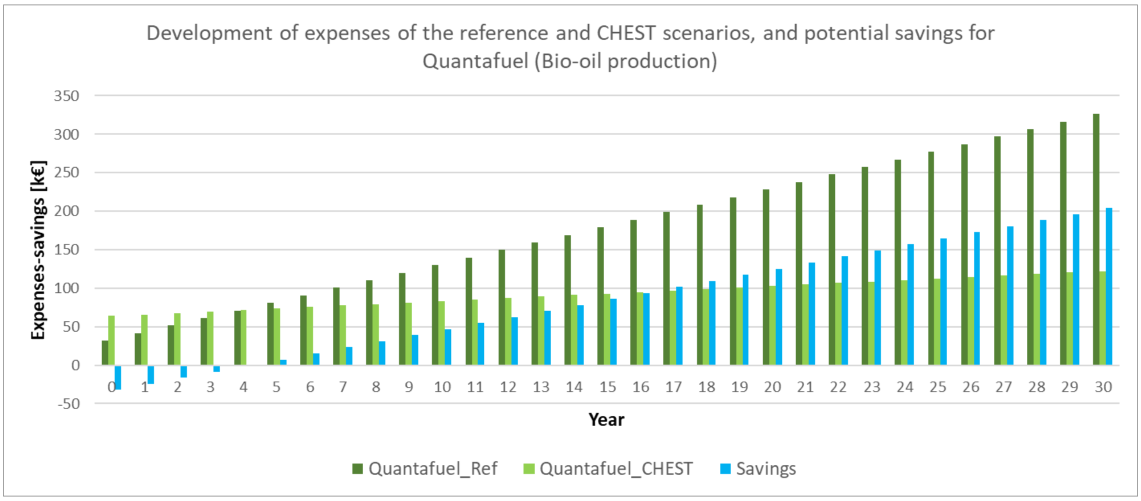

Figure 16. Development of the accumulated expenses for Quantafuel in the reference (dark green bars) and CHEST (light green bars) scenarios, and potential savings (light blue bars) over 30 years

With the initial assumptions of this business case, 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 about 6 years, and considerable savings compared with the reference scenario (all above 140% of their expenses after 30 years in the reference scenario). This initial 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 industry with a heat demand. Two factors can justify this choice:

- The industries with waste heat provide an energy input to the CHEST system for "free", and without them the heat should be produced somehow, which would be expensive. In exchange for their heat and a partial investment in the CHEST system, they get cooling in return
- It has previously been observed in Denmark that waste heat streams are used as a heat source to a heat pump, which then delivers higher grade heat to a district heating network[23]. In this case, the waste heat provider agrees to provide the heat for free and gets free cooling in return. In our business case, it is less interesting for the waste heat providers since they need to make a small investment, but the return on investment is however acceptable (happens within 4,5 years). The fact that their investment is lowered secures the access to the waste heat

REintegrate and Quantafuel have the same return on investment time and savings over expenses ratio after 30 years because their investments and yearly costs are directly proportional to their waste heat availability both in the reference and in the CHEST scenarios.

3.1.5. Sensitivity analysis

The previous section presents the results of a base case (using assumption presented in Table 5 to Table 11), which uses techno-economic assumptions that are representative of the energy sector in Denmark (district heating and electrical networks) in 2020-2021, and of the CHEST system studies made in the CHESTER project. The economic results of the base case, however theoretical, provide an idea that there could be a good business case using the CHEST system at the heart of a heating and cooling campus. In order to test the reliability of the results, some of the techno-economic parameters are varied, one at a time, in order to see

[23] In Høje Taastrup for instance, see [14]

the influence of the economic feasibility of the business case. The representative parameters which are varied are the following:

- Electricity price, varied from 20 €/MWh to 200 €/MWh (65,1 €/MWh in the base case)
- District heating - heat purchase price, varied from 20 €/MWh to 100 €/MWh (40 €/MWh in the base case)
- Number of operating hours of the CHEST system, varied from 4000 hours to 8000 hours (5600 hours in the base case)
- CHEST system CAPEX (excluding district heating pipes), varied from 80% to 150% (100% in the base case)
- Tax on electricity used to produce heat, set to half of the tax for regular electricity use: 59,3 €/MWh (instead of 0,537 €/MWh in the base case)

Figure 17 to Figure 20 present the results of the sensitivity analysis. The increase of electricity prices increases the return-on-investment time (ROI) for GLAS biogas (from 5,5 years to 8,2 years) and decreases it for REintegrate and Quantafuel (from 4,9 years to 3,2 years, see Figure 17). This effect is the result of the electricity used as an input for the heat pump of the CHEST system. In the reference scenario, GLAS biogas doesn't have electricity costs, while REintegrate and Quantafuel have the electricity costs associated with the use of dry coolers (respectively 18,5 k€/year and 9,8 k€/year in the base case), which are much higher than those of the heat pump in the CHEST scenario (respectively 10,4% and 5,5% of 36 k€/year, so 3,74 k€/year and 1,98 k€/year). The electricity produced by the ORC and sold in the CHEST scenario makes it even more interesting financially for REintegrate and Quantafuel when the electricity prices increase. An alternative business model could make use of a different electricity sale price (arranged through a Power Purchase Agreement for instance), which would benefit all industrial companies of the scenario. This hasn't been studied in the present business model but should be mentioned as an option.

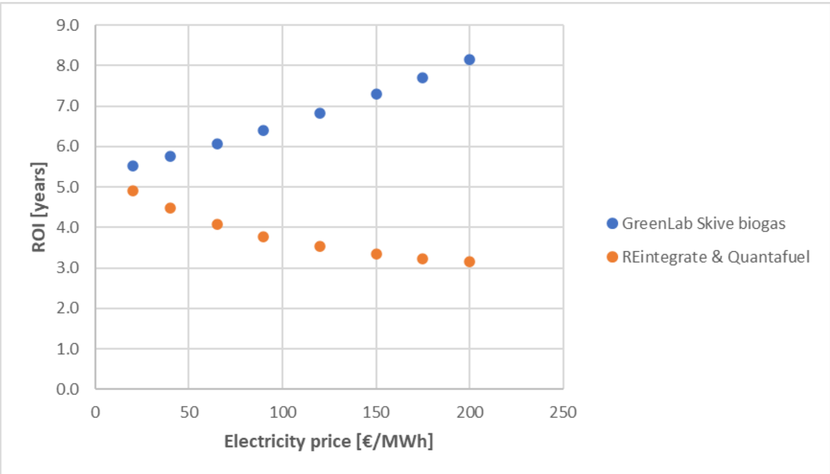

Figure 17. Dependence of the return-on-investment time with electricity prices for GLAS biogas, REintegrate and Quantafuel

The increase of heat purchase prices has a significant impact on the ROI for GLAS biogas (varying from 14,8 years to 2,1 years) and a much less significant one on REintegrate and Quantafuel (varying from 5,0 years to 3,6 years). In both cases, an increase in heat prices decreases the ROI (see Figure 18). For GLAS biogas, this is a direct consequence of the reference scenario, in which the annual costs are exclusively related to the purchase of heat. For REintegrate and Quantafuel, the decrease in return-on-investment time is indirectly related to the increase of annual costs for GLAS biogas: their share of the annual expenses of the reference scenario diminishes, which means that their annual expenses in the CHEST scenario diminish as well, making it more profitable for them to use the CHEST system.

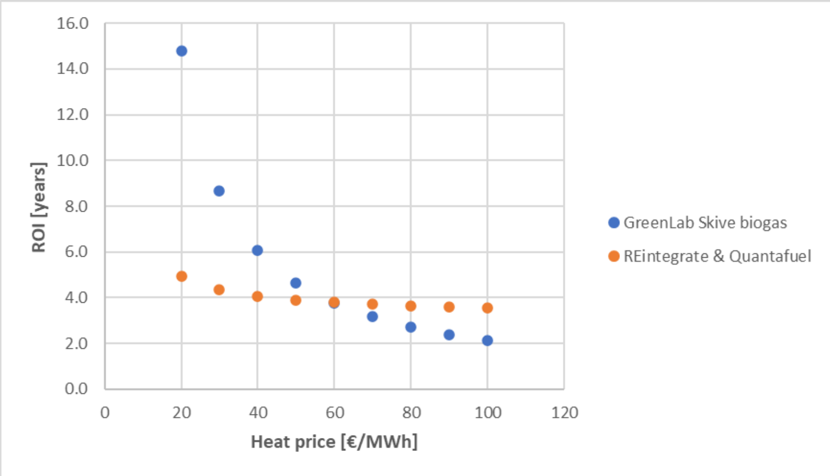

Figure 18. Dependence with heat prices of the return-on-investment time for GLAS biogas, REintegrate and Quantafuel

As expected (see Figure 19), the increase in CHEST system CAPEX increases the ROI for all industries (respectively from 4,8 years to 9,2 years for GLAS biogas and from 2,6 years to 7,8 years for REintegrate and Quantafuel, when increasing the base CAPEX from -20% to +50%). With higher investment costs, the business case for CHEST is less interesting, but remains profitable for all industries within less than 10 years. Lower investment costs give a preview of the increased profitability which can be expected in the future, where the technological costs for the ORC, heat pump and LTES will have decreased.

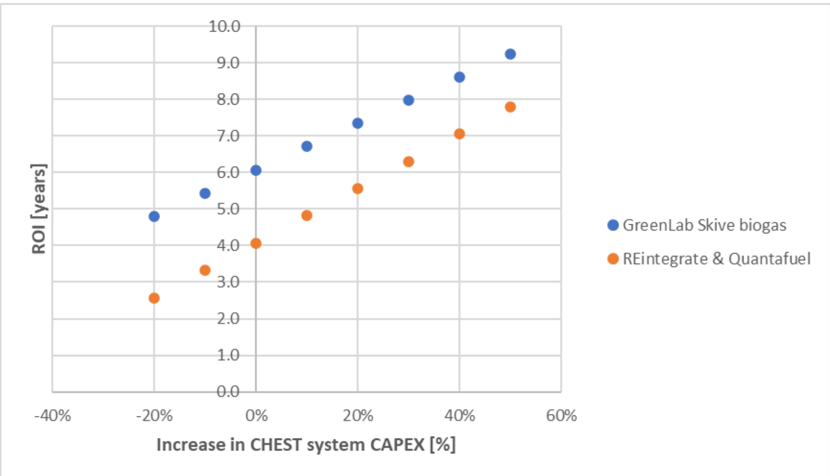

Figure 19. Dependence with CHEST system CAPEX of the return-on-investment time for GLAS biogas, REintegrate and Quantafuel variation (increase or decrease compared to the base case investment cost of 932 k€)

Figure 20 shows that the increasing number of operating hours decreases the ROI for all industries (respectively from 8,5 years to 4,2 years for GLAS biogas and from 5,7 years to 2,8 years for REintegrate and Quantafuel when increasing from 4000 operating hours to 8000 hours). This was expected: the more the CHEST system is used, the better the payback.

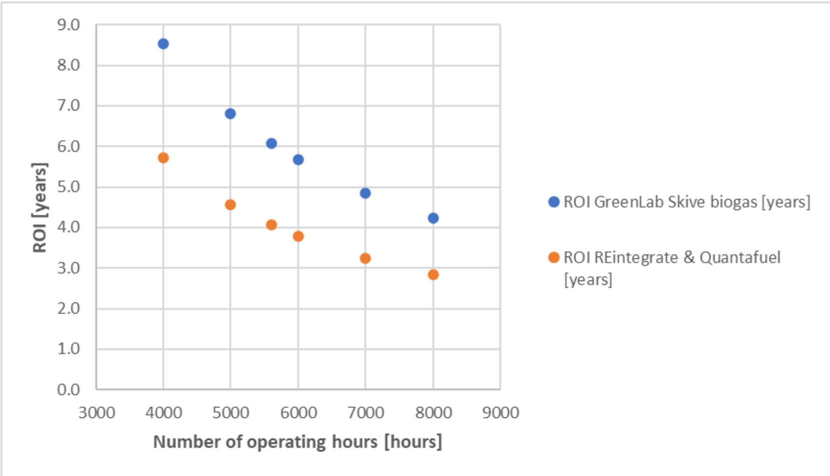

Figure 20. Evolution of the return-on-investment time for GLAS biogas, REintegrate and Quantafuel with CHEST system number of operating hours

If the electricity prices increase, the heat prices are likely to also increase, and the negative effects of the profitability of the business case for GLAS biogas due to electricity price increase might be compensated by the positive effects of the heat price increase. Just to illustrate/test this phenomenon, an increase in both prices by 50% compared with the base case provides the results from Table 20. The resulting heat purchase price is 60 €/MWh, the resulting electricity price is 97,8 €/MWh, and these prices improve the economy of the CHEST scenario for all the industries (return-on-investment time decreases from 6,1 years to 4,0 years for GLAS biogas, and from 4,1 years to 3,4 years for REintegrate and Quantafuel). It is hard to say if a 50% increase in electricity prices would be met in practice by a 50% increase in heat prices, therefore the same calculation was made assuming a 50% increase in electricity prices together with a 10% increase in heat prices (44 €/MWh). This provides the results showed in Table 21, which exhibit an improvement of the economic cases of all industries compared with the base case (return-on-investment time decreases from 6,1 years to 5,8 years for GLAS biogas, and from 4,1 years to 3,6 years for REintegrate and Quantafuel).

Table 20. Economic KPIs for the industrial companies of the initial business case, where the heat and electricity purchase prices have both been increased by 50%

Industrial company / KPI [unit]	GLAS biogas	REintegrate	Quantafuel
ROI compared to reference [year]	4,0	3,4	
Total savings at year 30 [k€]	4825	477	253
Savings over expenses ratio at year 30 [-]	205%	201%	

Table 21 Economic KPIs for the industrial companies of the initial business case, where the electricity purchase price has been increased by 50% and the heat purchase price has been increased by 10%

Industrial company / KPI [unit]	GLAS biogas	REintegrate	Quantafuel
ROI compared to reference [year]	5,8	3,6	
Total savings at year 30 [k€]	3074	442	234
Savings over expenses ratio at year 30 [-]	134%	162%	

The last sensitivity parameter which can be tested is the effect of changing the tax on electricity for heat production. In Denmark, a special incentive to use electricity to produce heat was put in place in 2020. It reduces the taxes to close to 0 (0,573€/MWh). In most countries, industries which use electricity don't benefit from such a significant tax cut, but simply lower electricity taxes. To see the effect of changing this tax, Table 22 presents the results of using a tax of half the tax on regular electricity from the base case (118,7/2 = 59,3 €/MWh) instead of the Danish tax from 2020. This has a negative impact on the economy of the business case: the return-on-investment time increases from 6,1 years to 7,8 years for GLAS biogas, and from 4,1 years to 5,2 years for REintegrate and Quantafuel. This is a consequence of the increase in CHEST system annual operating costs, through the increase of the electricity purchase costs for the heat pump. These results show the importance of having a favorable taxing scheme to make the CHEST storage solution a good business case.

Table 22. Economic KPIs for the industrial companies of the initial business case, where the tax on electricity used to produce heat has been set to 50% of the regular electricity tax

Industrial company / KPI [unit]	GLAS biogas	REintegrate	Quantafuel
ROI compared to reference [year]	7,8	5,2	
Total savings at year 30 [k€]	2074	285	151
Savings over expenses ratio at year 30 [-]	73%	86%	

3.1.6. Disclaimer

The numbers obtained in this business case are not those of an actual business case (in practice, industries would have invested in the CHEST system using loans, specific business arrangements and contracts for instance), but were rather used to identify a business opportunity. The techno-economic analysis was simplified, using return on investment time based on growing expenses with the lifetime of the different scenarios.

3.2. CHEST vs. pumped hydro

Pumped hydro storage (PHS) is the most implemented technology for the storage of electric energy in the form of potential energy. A PHS consists of two water basins at different heights, connected by pipes in which water can flow up-/downwards, a turbine connected to an electricity generator, a pump moved by an electric engine, transformers and connections to the grid. The amount of stored energy is proportional to both the height between the two basins and the volume of water contained in the upper basin. The primary intent of PHS is to provide energy during daily peaks. Water is usually pumped to the upper basin when electric energy price is lower, or when an overproduction of energy (possibly from renewable sources) is available: in this last case, renewable electric energy is used to feed the pump engine and converted into potential energy of water that is moved to the upper basin. When electric demand peaks and exceeds production on the grid, water flows down through the turbine generating electric energy.

A new PHS, including dams, is characterized by high capital cost and a long construction time. The retrofitting of an existing hydropower plant to become a PHS is less capital-intensive and can require 2-3 years [1]. Furthermore, PHS viability is strictly connected to the local topology, hence restricting the application of these storage plants to mountainous areas or regions with significant differences in altitude and large availability of water.

The report published by the Commission “Study on energy storage- Contribution for the EU security of supply” quantifies the requirements for electricity storage deployment in the EU under different scenarios. To achieve the 100% RES target by 2050 the report estimates the electricity storage needs in 780 TWh. The dominating technology nowadays providing electricity storage is PHS, accounting for more than 98% of the installed capacity, according to the JRC that on 2013 counted 29 TWh of discharging and 38 TWh for charging. This, however, is a limited resource; JRC estimates a maximum potential in Europe of 3.5 times the current installed capacity. Comparing the requirements (780 TWh) and the potential of pumped hydro (around 120 TWh), we see that there is a technological gap of around 660 TWh to be filled in order to meet the Commission objectives for the coming decades

Neglecting the supply of relatively low-T heat to district heating and other end users, CHEST system can act as a full Power-to-Power storage system, hence operating exactly like a PHS does. In particular, in the CHEST prototype, HP (heat pump), high-T storage and ORC (Organic Rankine Cycle) engine respectively correspond to pump, upper basin and turbine in PHS, while heat in CHEST replaces water used as a vector in PHS.

In this task, the typical operation on an annual base of a PHS owned by Gruppo Iren in North-West of Italy is compared with the Power-to-Power operation of CHEST under different techno-economic scenarios and adopting different operating logics.

Figure 21 - Location of the PHS plant. The same location was chosen for the simulation of the CHEST system

3.2.1. Technical data and assumptions

CHEST ORC has a nominal power of 5-50 MW. The lower bound was chosen based on the simulation results of CHESTER deliverable D2.2.

The HP/ORC ratio is set equal to 2:1, as an average value of this parameter that can be fully representative of all the possible working configurations, as outlined in Deliverable 6.5. So, the HP has a nominal power of 10-100 MW.

Concerning the production profile of PHS, the typical normalized profile of the real power plant owned by Gruppo IREN (Figure 22) was rescaled in order to keep the nominal power of the turbine equal to the nominal power of the ORC.

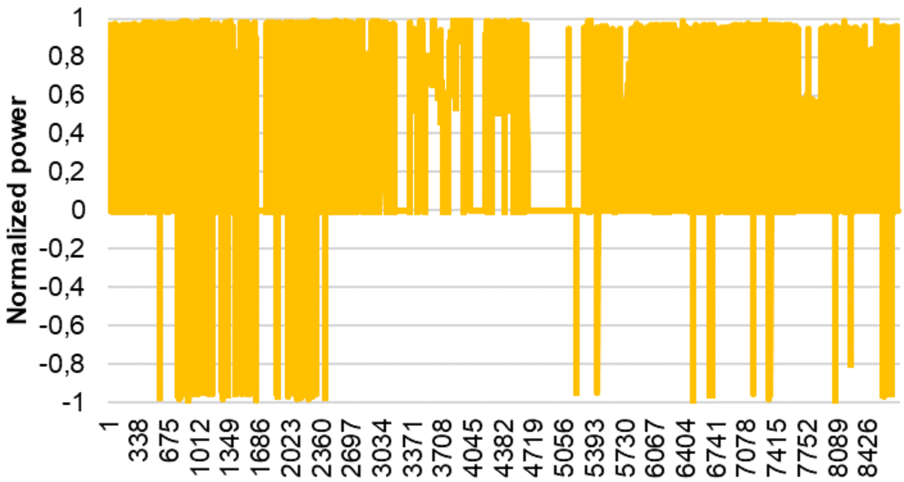

Figure 22 - Typical normalized power production profile of the real PHS plant owned by Gruppo IREN (positive values: turbine operation; negative value: pump operation)

As a further remark, a waste heat supply at a temperature consistent with CHEST HP operation is assumed to be available for free on CHEST site: the system is assumed to be thermally integrated at the heat pump side and able to discharge to ambient temperature.

A sensitivity analysis on the following performance indexes was carried out:

- COP (Coefficient of Performance) of HP spans from 4 to 5,4, with the latter value corresponding to a temperature of the heat source of 80 °C, based on the performance map of the HT-HP for Butene (see CHESTER deliverable D2.1);
- the efficiency of ORC (Organic Rankine Cycle) engine spans from 15 to 21%. The lower value was derived from the CHESTER deliverable D2.1, based on the performance map of the ORC for butene, assuming condensation to the environment.

Since the timescale of the thermal energy storage (TES) is assumed to be below 24 hours (i.e., the multi-daily or seasonal operation is excluded, see “Operating logics” section), thermal losses through the TES walls are neglected. The size of the high-T TES was also varied depending on the simulated scenario.

Table 23 - Technical data and assumptions for the simulation of PHS vs. CHEST operation

Parameter	Value	Unit	Notes
HP-ORC capacity ratio	2:1		*
Nominal size of turbine in PHS	5	MW	Varied between 5 and 50 MW
Nominal size of pump in PHS	10	MW	Varied between 10 and 100 MW
Nominal size of the ORC in CHEST	5	MW	Varied between 5 and 50 MW
Nominal electric capacity of the HP in CHEST	10	MW	Varied between 10 and 100 MW
COP of HP	5,4	-	Varied between 4 and 5,4
Thermal losses of TES	negl.		
Latent heat ratio	50%		*
Efficiency of ORC	15%		Varied between 15% and 21%
Size of PV plant	10	MW	Varied between 10 and 100 MW

* The HP/ORC ratio and latent heat ratio are set as average values of the parameters listed in Deliverable 6.5 to be fully representative of all the possible configurations and setups of the CHEST system.

3.2.2. Operating logics

In all the operating logics listed hereunder, the ORC power is modulated in order to close the energy balance of the thermal energy storage (TES) on daily scale, i.e., thermal energy generated by the heat pump and stored in TES equals the amount of thermal energy sent to the ORC on any day of the year. The HP is modulated, as well, in order to fulfill the mentioned constraints.

- Logic 1a – synchro. The CHEST system is connected to the grid and is “synchronous” with the pumped hydropower plant. Renewable energy is assumed to be fully available on the grid and purchased. Charging phase: HP operates when the pump of the hydropower plant is on. Discharging phase: ORC switches on when the turbine of PHS is operating. If the PHS plant stops during a whole day, the CHEST system is stopped as well.
- Logic 1b – synchro. A dedicated PV plant (radiation data for the location of the PHS is downloaded from PVGIS platform) with rated power equal to the nominal size of the HP is installed to feed the CHEST system. Charging phase: HP operates when the pump of the hydropower plant is on,

withdrawing the effective power available from the RES plant at that moment. Discharging phase: ORC switches on when the turbine of PHS is operating. If the PHS plant stops during a whole day, the CHEST system is stopped as well.

- Logic 2 – RES-driven. The operation of the CHEST system is totally ruled by the availability of energy from the dedicated PV plant. Charging phase: HP operates when RES is available from the dedicated plant (the HP operates with exactly the power that the PV plant generates at that time). Discharging phase: ORC switches on when the PV plant is not operating.
- Logic 3 – Cost optimization. A switch price is introduced to increase the profit from the sale of electric energy produced by the ORC during the discharging phase. Charging phase: HP operates when RES is available from the dedicated plant. Discharging phase: ORC switches on when electric energy price is higher than the switch price, i.e. the sale of electricity to the grid is more profitable, and the power rate is chosen constant during operation and determined based on closing the energy balance of the TES on a daily basis.

Furthermore, as a second constraint of the simulation, the power at which the HP and ORC operate is clearly kept below their nominal values and excess production from the dedicated PV plant is sold to the grid.

3.2.3. Economic scenarios and financial parameters

In all the simulations, local electricity prices valid in 2019 in the "North-Italy" zone of the Italian Power Exchange were applied (Figure 23) as a reference scenario. These prices consisted of the hourly day-ahead market prices. The electricity buy add-ons to run the HP in logic 1 and the pump of PHS, which consist of grid fees, taxes, etc. were taken into account as a +200% increase of the electric energy market price (e.g., when the market price is 50 €/MWh, the total price for HP electricity is 150 €/MWh). The profile after 2020 was not considered as a reference due to significant variations caused by COVID-19 pandemics and recent geopolitical imbalances due to the Russian invasion of Ukraine. However, a further sensitivity analysis to assess the effect of different values of electric energy price (taking into account the recent evolutions of the energy market) on the internal rate of return of the investment was carried out. The uncertainty regarding the evolution of future electricity prices is very high, they could come back again to similar prices we had in 2019, they can keep at current values or they can even increase. The approach used in this study (using reference values of 2019 and complementing the study with a sensitivity analysis considering a maximum electricity price of 500 €/MWh) covers all the possible scenarios.

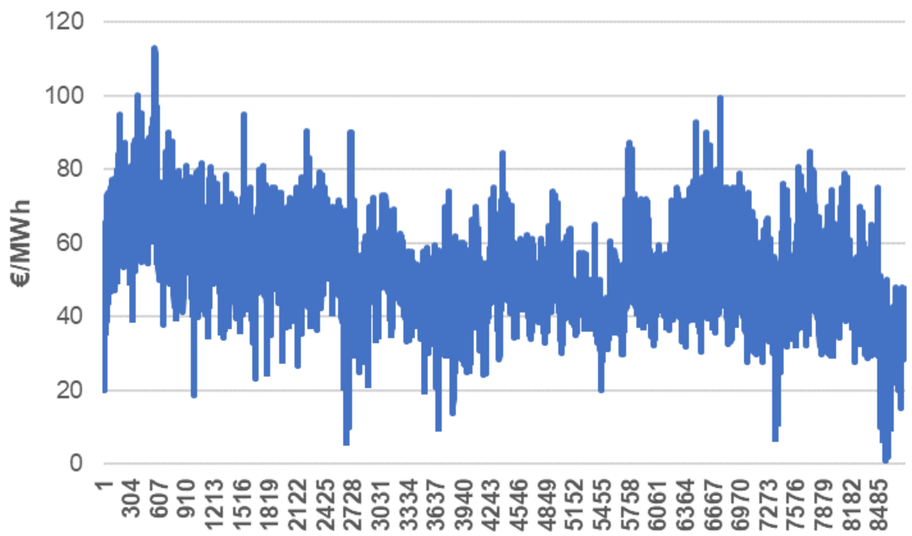

Figure 23 - Electric energy price in North Italy (2019)

In logic 3, as already mentioned, the switch-on and -off of the ORC was determined by the difference between the hourly market price and an arbitrary value of a switch price. A sensitivity analysis was carried out on the switch price, analyzing the effect of its variation between 0 and 80 €/MWh (0-150% of the average cost of electricity) on the techno-economic key performance indicators.

Two different scenarios were introduced to account for the reduction of capital costs expected for CHEST components (and communicated by the technical partners of the CHESTER consortium):

- current market;
- future market (long-term, i.e. 2040-50).

Concerning the costs of the system components in PHS and CHEST system, the following assumptions were introduced:

- For large hydropower plants in OECD countries, capital costs are about 2400 $/kW (ref. 2018, i.e. about 2000 €/kW). Depending on their configuration and use, PHSs may be twice as expensive as an unpumped hydropower system, i.e. about 4000 €/kW. Fixed O&M are about 1-2% of investment costs, while variable O&M depends on electric energy prices [1]. No significant technology advance or cost decrease is expected, since hydropower and water pumping are established technologies: hence, the mean values of these costs (3000 €/kW and 1,5%) are assumed constant in the two scenarios introduced before.
- For the CHEST system, the assumed investment costs, O&M costs and lifetimes of the components were agreed with partners.
- Investment and O&M costs of the PV plant (reported hereunder for the sake of completeness) were excluded from the analysis.

Table 24 summarizes the assumptions and the key input economic data for the analysis agreed with the CHESTER partners. Variable O&M deriving from the purchase and sale of electric energy from/to the grid were considered; the participation in the market of ancillary and regulation services was not considered. A system lifetime of 30 years was assumed.

Table 24 - Economic assumptions and data for the simulation of PHS vs. CHEST operation

PHS		
Specific CAPEX (€/kW)	3000	
O&M (%CAPEX)	1,5%	
CHEST		
	Scenarios	
SPECIFIC CAPEX	**Current**	**Future**
HP (€/kWth)	350	250
ORC (€/kWe)	1000	850
LTES (€/kWh)	100	50
STES (€/kWh)	3	3
O&M (€/MWh)	**Current**	**Future**
HP	5	5
ORC	10	10
LTES/STES	5	5

3.2.4. Key techno-economic performance indicators

Simulations using MS Excel® were carried out to assess the performance of CHEST prototype when replacing a PHS plant under different operating logics with the aim of storing and shifting in time large amounts of renewable energy.

The time resolution of the simulation was 1 hour. Energy balances were performed on the system and single components and the following key performance indicators were computed on an annual base, taking into account the aforementioned limitations and constraints on power rating and duration of the charge-discharge cycle of TES:

- $E_{E,in}$: electric energy feeding the HP and either withdrawn from the grid in logic 1a, or provided by the dedicated PV plant in other logics;
- $E_{E,out}$: electric energy produced by the ORC and sold to the grid;
- $E_{E,PV,grid}$: excess production of PV dedicated plant (in logics 1b, 2 and 3) that is sold to the grid and does not feed the HP due to limitations on the power rate of ORC and HP;
- $E_{E,PV,curt}$: excess production of PV dedicated plant (in logics 1b, 2 and 3) that is curtailed since it cannot be absorbed by the HP due to the constraints and limitations on power rates and TES;
- η_{rt}: roundtrip efficiency of the CHEST system, i.e., Power-to-Heat-to-Power efficiency, computed on an annual base as the ratio between the electric energy leaving the system ($E_{E,out}$) and the electric energy used to run the HP ($E_{E,in}$). Since no thermal losses are expected between the HP and the ORC and since the model is based on constant technical parameters, roundtrip efficiency coincides in any moment with the product of the COP of HP and the efficiency of ORC;
- $E_{th,TES}$: thermal energy stored in the storage. Due to the constraint on the 24-h cycle, the amount of heat charged by the HP in the TES coincides with the thermal energy feeding the evaporator in the ORC during discharging phase;
- $P_{th,TES}$: size (in terms of energy, MWh) of the thermal energy storage;
- CF_{HP}: capacity factor of the HP, given by the ratio between $E_{E,in}$ and the energy that would be fed if it worked constantly at its rated power during the whole year;

- CF_{ORC}: capacity factor of the ORC, given by the between $E_{E,out}$ and the maximum production of the ORC if it worked at its rated power during the whole year.

Concerning economic results, a pre-taxation cash flow analysis was carried out considering the different operating logics and the economic scenarios for the CHEST system. The feasibility of the system was assessed on asset side basis, considering a 100 % equity contribution. In order to “bypass” the effect of significant variations of the discount rate *i* due to market conditions, the internal rate of return (IRR, i.e. the value of the discount rate that ensures a breakeven at the end of plant lifetime – or, in other words, net present value equal to zero) of PHS vs. CHEST was assessed as a KPI of the profitability of the investment:

$$IRR = i: \sum_{k=1}^{n_{life}} \frac{FCF_k}{(1+i)^k} - |TOC| = NPV = 0 \qquad \text{(Eq. 1)}$$

where FCF_k is the free cash flow at k^{th} year and TOC is the Total Overnight Cost of the system.

The higher the IRR, the more profitable the investment is. If the IRR is negative, no profit can be expected during the plant lifetime.

3.2.5. Results of the simulations

This section presents the results of the simulations run with a CHEST system characterized by an ORC nominal power of 5 MW. The four different operating logics (1a, 1b, 2 and 3) were considered, keeping the same limitations and constraints explained before.

Figures hereunder summarize in a graphical way the HP/ORC profile of the CHEST system (HP: negative values / ORC: positive values) and the operation (i.e., stored heat) of the TES on an annual basis.

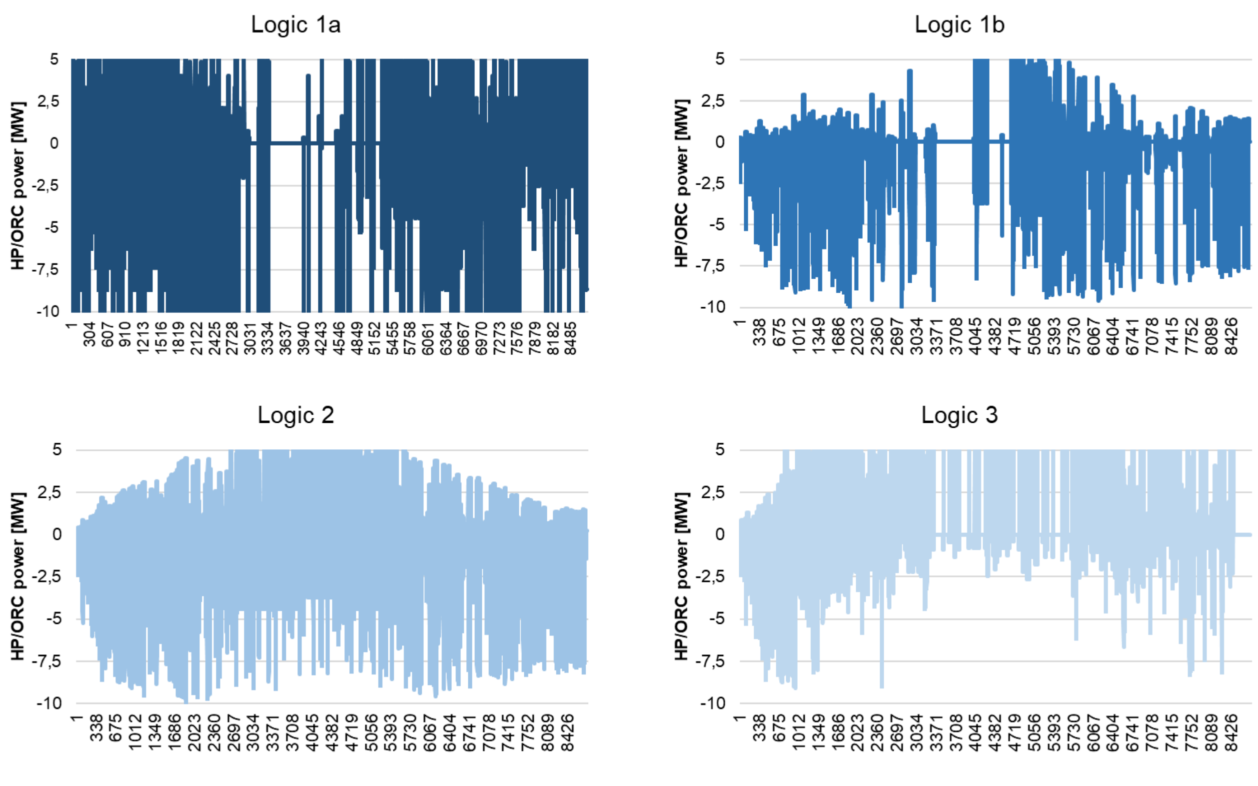

Figure 24 - HP/ORC operating profile of CHEST system under different logics (in logic 3, switch price: 55 €/MWh)

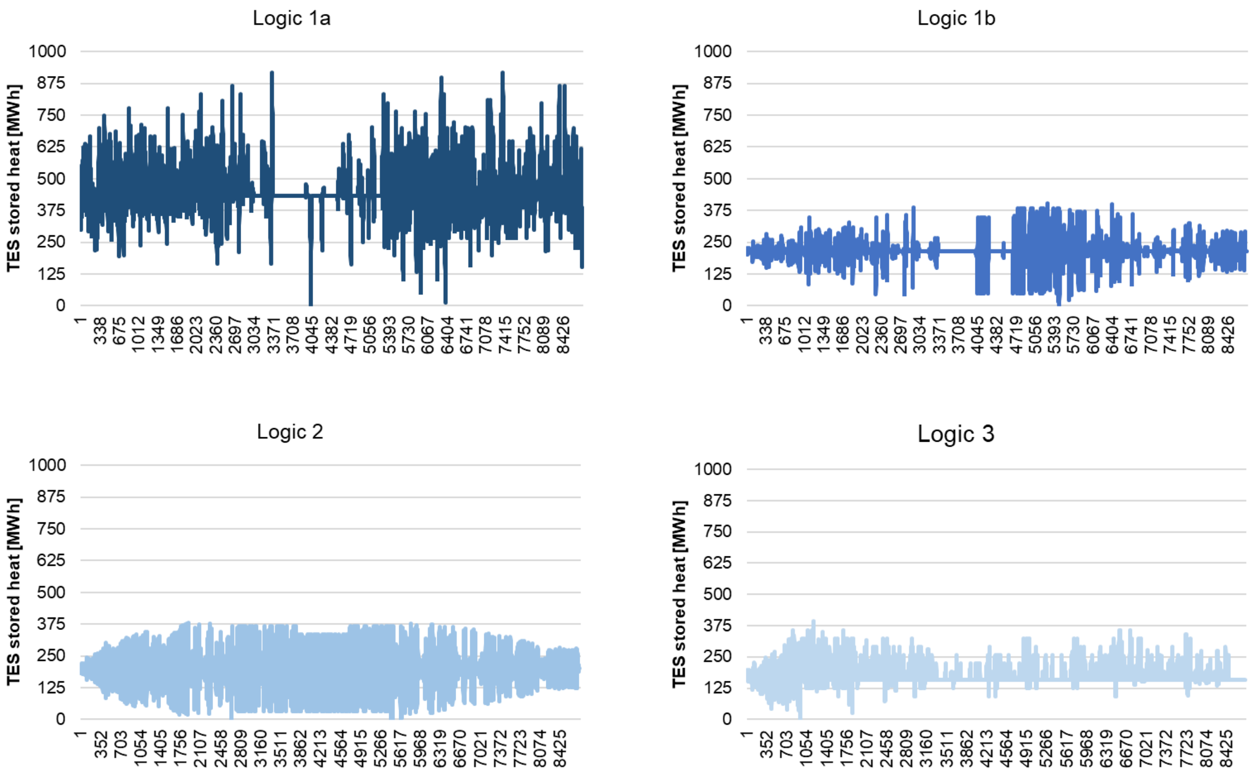

Figure 25 - TES profile on annual base under different logics (in logic 3, switch price: 55 €/MWh)

In logic 1a, HP and ORC operate respectively when the pump or turbine of the PHS is on, purchasing the electric energy to run the HP directly from the grid (assuming that in those time slots renewable energy is fully available on the grid). This logic maximizes the capacity factors (CF) of HP and ORC (18,1% and 29,3%, respectively) and, thus, the amount of energy that is stored and shifted in time. CHEST system operating with this logic may be of particular interest in grid portions with a very high penetration of renewable energy sources: in/out fluxes from/to the grid may be controlled and optimized in order to maximize the use of renewable energy supply, store it when exceeding grid loads (hence, avoiding curtailment) and shifting in time to fulfill demand peaks.

Logic 1b presents the same HP/ORC profile of logic 1a, but the amount of energy used to run the HP depends on the productivity of a dedicated PV plant. Hence, CHEST system operating according to this logic accomplish the same mission as under logic 1a, but a further constraint on the availability of electric energy is introduced: for this reason, CFs of HP and ORC decrease respectively to 6,7% and 10,9%.

Under logic 2, the CHEST operation is not dependent on the PHS profile but is solely ruled by the productivity of the dedicated PV plant. Hence, in other configurations and scenarios (see business model #3), this logic may be adopted for time-shift of the energy produced by an oversized grid-connected RES plant: during sunlight hours, the energy production of the PV plant is used to run the HP. In this model, the energy produced by the PV plant is used to run the HP, whereas PV overproduction is sold to the grid. Heat stored is then used in the evaporator of the ORC at night to generate electric energy that is sold to the grid. The HP/ORC profile undergoes seasonal variations: in wintertime, the power rate of ORC to close the daily balance of thermal energy in TES decreases since it operates for a higher number of hours. In summertime, HP operates at its maximum power for longer time due to longer daytime and higher irradiance; however, shrinking the discharge phase of TES to a smaller time span at night may force ORC to work at a power rate (to reach daily balance of TES) that exceeds its nominal size. This operating point is not valid: the constraint introduced forces ORC to work at its power rate, at most. This reduction of ORC power rate implies a reduction of the amount of heat discharged at night to run the ORC (positive values in Figure 26). Iteratively, to close the daily balance of TES, the running profile of the HP is rescaled down. The share of PV energy that is not used to run the HP is then sold to the grid (negative values in Figure 26).

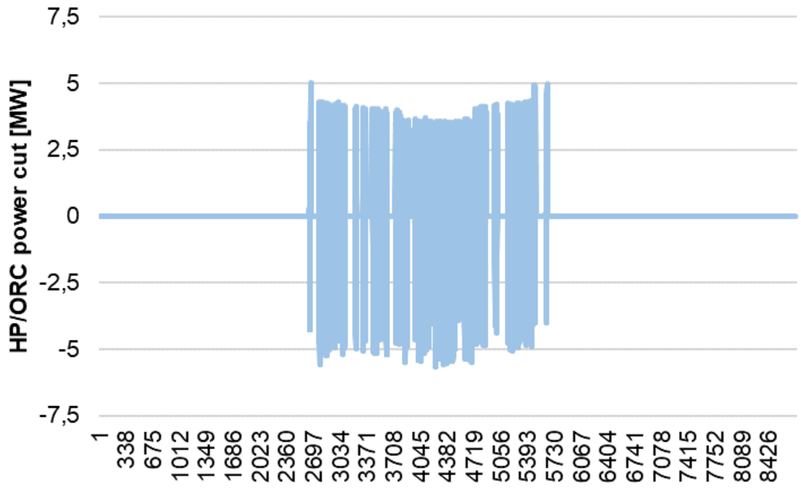

Figure 26 - Effect of the constraint on ORC power rate under logic 2

Logic 3 aims to maximize the profit from the sale of electricity, shrinking the production of energy by the ORC to the hours in which the market price exceeds a certain switch price. The value of the switch price is arbitrary in this analysis: a value of 55 €/MWh was chosen since it is almost equal to the average value of the market price of electric energy in 2019 (cf. Figure 23). Furthermore, this value ensures the same CFs as in logic 1b, hence ensuring that the Power-to-Power mission is accomplished also in this case. Because of this choice, the cut of ORC power rate (i.e., the forced reduction of power rating to the nominal ORC power rate, at most) is more significant and is experienced in a wider period of the year, and not only in summertime. A sensitivity analysis to assess the effect of the variation of this parameter on techno-economic indicators was carried out and is presented in the next section.

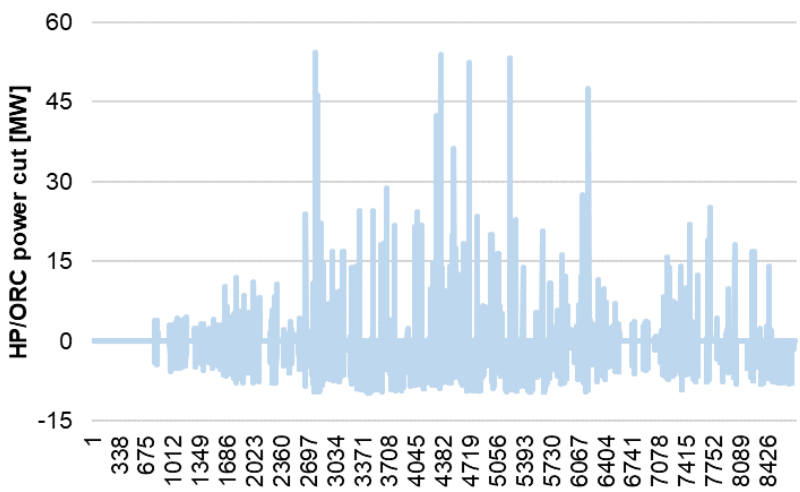

Figure 27 - Effect of the constraint on ORC power rate under logic 3 (switch price: 55 €/MWh)

Table 25 summarizes the technical performance indicators of the CHEST system under the different logics and keeping the default values of the parameters in Table 23.

Table 25 - Technical output of the simulations of CHEST system under different logics

Parameter	Unit	Logic 1a	Logic 1b	Logic 2	Logic 3
$E_{E,in}$	GWh/y	15,83	5,86	13,67	5,76
$E_{E,out}$	GWh/y	12,82	4,75	11,08	4,67
$E_{E,in,PV}$	GWh/y	15,83	5,86	13,67	5,76
$E_{E,PV,grid}$	GWh/y	0,00	8,38	0,56	8,48
$E_{th,TES}$	GWh/y	85,49	31,64	73,84	31,11
$P_{th,TES}$	MWh	918,00	402,46	380,21	391,49
$\eta_{roundtrip}$	%	81,0%	81,0%	81,0%	81,0%
CF_{HP}	%	18,07%	6,69%	15,61%	6,58%
CF_{ORC}	%	29,28%	10,84%	25,29%	10,65%

3.2.6. Logic 3: the effect of the switch price

In this section, the analysis focused on the effect of the switch price on the operation of the CHEST system and its influence on the HP/ORC switch-on and -off: recalling that the mean value of market price of electric energy in the reference year (2019) in North Italy was about 55 €/MWh, switch price was varied between 0, 40, 60 and 80 €/MWh in the analysis.

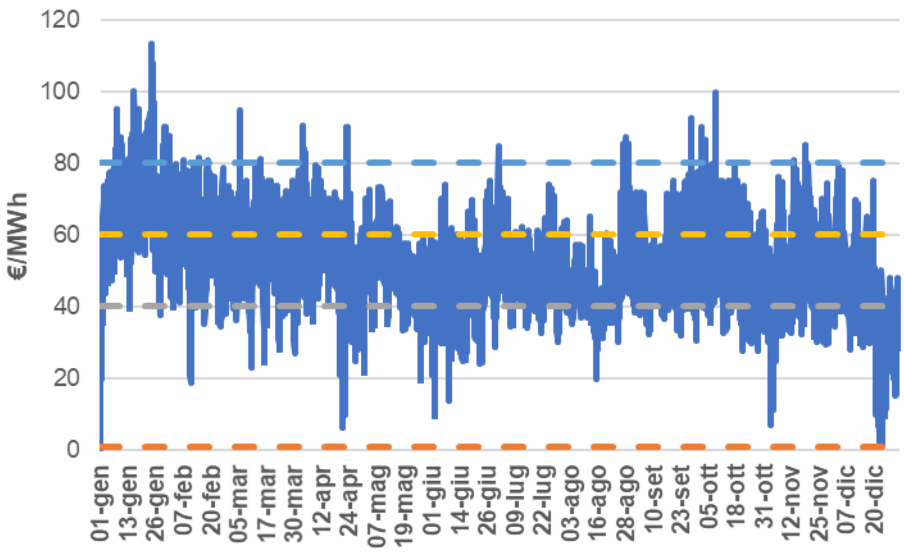

Figure 28 - Variation of the switch price in logic 3 against the day-ahead electricity price profile of 2019

Remark that considering switch price equal to zero coincides with logic 2, since the further constraint about the switch-on events of the ORC decades.

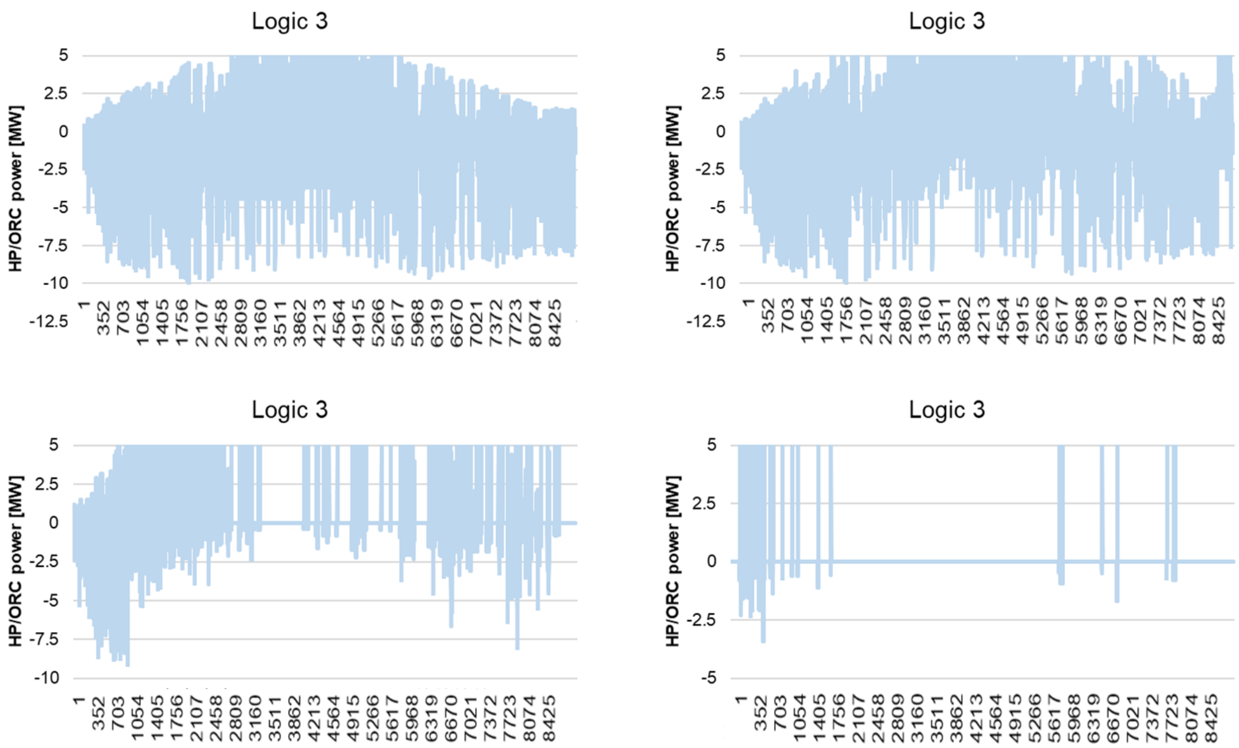

Figure 29 - HP/ORC operating profile. Top left: 0 €/MWh; top right: 40 €/MWh; bottom left: 60 €/MWh; bottom right: 80 €/MWh

As already stated, in logic 3, ORC switches on when the market price of electric energy exceeds the assumed value of switch price. When the switch price increases, overlapping the annual profile of the electric energy market price, more and more time slots throughout the year are excluded for the operation of ORC: notice the difference in HP/ORC profile (in particular, in the months of June and December) when increasing the switch price from 0 to 40 €/MWh in Figure 29. Further rise of switch price determines a strong limitation of ORC switch-on events to few periods of the year, and consequently reducing the share of electric energy provided by the PV to the HP to ensure the correct balance of thermal energy. This dramatically reduces the CF of the whole system and consequently prevents CHEST system from accomplishing its Power-to-Power task, i.e., the shift of power produced from PV during sunlight hours to nighttime. This means that switch price should not exceed a certain level, otherwise the CHEST system would be progressively bypassed.

In fact, notice in Table 26 and in Figure 30 how the electric energy provided by the PV to the HP rapidly decreases when switch price exceeds the value of 40 €/MWh, i.e. approaching the mean values of the profile in Figure 28.

For these reasons and what already explained in the previous sections, a default value of 55 €/MWh was set for the switch price in logic 3.

Table 26 - Effect of switch price on the technical parameter of the CHEST system in logic 3

Switch price (€/MWh)	0	10	20	30	40	50	60	70	80
$E_{E,in}$ (GWh/y)	13,67	13,67	13,65	13,43	11,89	7,93	4,01	1,97	0,32
$E_{E,out}$ (GWh/y)	11,08	11,08	11,06	10,88	9,63	6,42	3,25	1,59	0,26
$E_{E,in,PV}$ (GWh/y)	13,67	13,67	13,65	13,43	11,89	7,93	4,01	1,97	0,32
$E_{E,PV,grid}$ (GWh/y)	0,56	0,56	0,58	0,81	2,35	6,31	10,22	12,27	13,91
$E_{th,TES}$ (GWh/y)	73,84	73,84	73,72	72,50	64,21	42,81	21,67	10,63	1,75
$P_{th,TES}$ (MWh)	380,21	380,21	401,32	400,00	433,33	420,83	323,01	221,12	172,64
$\eta_{roundtrip}$	81,0%	81,0%	81,0%	81,0%	81,0%	81,0%	81,0%	81,0%	81,0%
CF_{HP}	15,61%	15,61%	15,58%	15,33%	13,57%	9,05%	4,58%	2,25%	0,37%
CF_{ORC}	25,29%	25,29%	25,25%	24,83%	21,99%	14,66%	7,42%	3,64%	0,60%

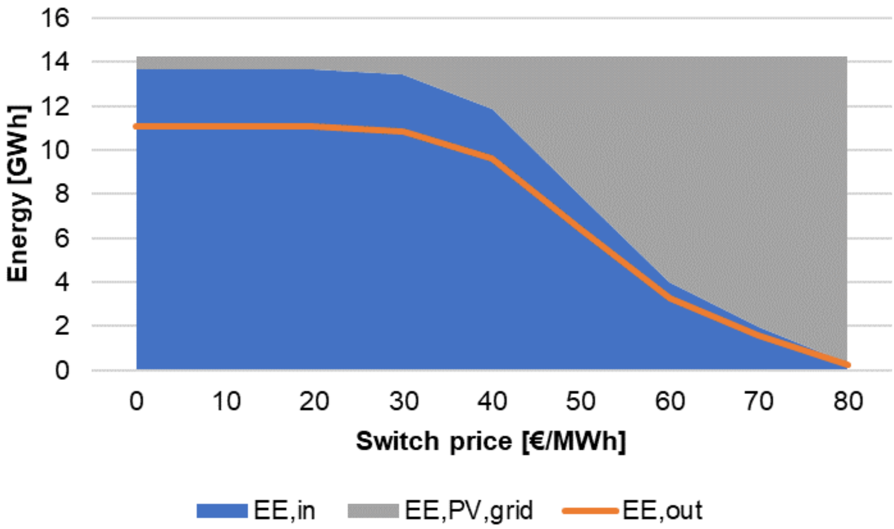

Figure 30 - Variation of the CHEST energy balance with the switch price under logic 3

3.2.7. Sensitivity analysis

Before assessing the economic feasibility of the CHEST system in its default technical configuration, the effect on technical KPIs listed in the previous sections were assessed. In particular, the analysis focused on the variation of the HP Coefficient of Performance (COP) between 4 and 5.4 and of the efficiency of ORC between 15 and 21%.

Keeping the constraints and limitations about the power rate and the energy balance of the TES and considering the default size of the ORC (5 MW) and HP (10 MW_e), Table 27 summarizes the results of the sensitivity analysis under different operating logics.

The increase of the efficiencies of the two components implies a rise of roundtrip efficiency, since intermediate losses of TES are neglected due to its daily timescale. In default conditions, roundtrip efficiency equals 81%.

A higher COP of the HP has the double effect of:

- reducing the HP charging power and, as a consequence also of the imposed constraints, reducing the withdrawal of the electric energy from PV plant used to run the HP (hence increasing the share of electric energy that is directly injected in the grid);
- increasing the thermal energy available in the TES. However, the aforementioned constraints avoid the uncontrolled increase of the thermal level of the TES, limiting the growing discharge rate to feed the ORC evaporator: to save the energy balance, also the incoming heat is capped, limiting the HP power rate.

These two conflicting effects are evident in the trend of the CFs of HP and ORC: because of the lower power input due to COP increase, the capacity factor of HP decreases. Instead, the CF of ORC increases.

For these reasons, thermal energy that is totally exchanged by TES increases when COP increases. As well, higher charge/discharge rates increase the size [MWh] of the TES.

A higher efficiency of the ORC has the double effect of:

- reducing the amount of thermal energy supplied by the TES to the ORC evaporator on those days when the ORC works at or close to its nominal power (e.g. in summertime; cf. box 1 in Figure 31). Since less heat should be supplied to TES in order to close the daily balance, in this period the HP can operate at partial load, hence increasing the share of PV energy that can be directly sold to the grid;
- increasing the power output of ORC on days when it operates at partial load (e.g. in mid-seasons; cf. box 2 in Figure 31). In this situation, heat demand to TES may be constant or even decrease according to the variation in the ORC power output. In any case, the power rate of HP does not increase.

For these reasons, the same trends of CFs as in case of increase of HP COP are expected. Instead, the size and the energy exchanged by the TES decrease.

Table 27 - Sensitivity analysis. Effect of system efficiency on the technical KPIs

			HP COP											
			4				4,7				5,4			
		Logics →	1a	1b	2	3	1a	1b	2	3	1a	1b	2	3
ORC efficiency	15%	$\eta_{roundtrip}$	60,0%				70,5%				81,0%			
		E_E to HP (GWh/y)	18,8	6,0	14,2	6,9	17,2	6,0	14,1	6,3	15,8	5,9	13,7	5,8
		$E_{E,PV}$ to grid (GWh/y)	0,0	8,2	0,0	7,4	0,0	8,3	0,1	8,0	0,0	8,4	0,6	8,5
		$E_{th,TES}$ (GWh/y)	75,1	24,1	56,9	27,5	81,0	28,1	66,4	29,5	85,5	31,6	73,8	31,1
		$P_{th,TES}$ (MWh)	793,3	306,2	309,8	317,2	886,7	356,4	349,9	359,1	918,0	402,5	380,2	391,5
		CF_{HP}	21,4%	6,9%	16,3%	7,8%	19,7%	6,8%	16,1%	7,2%	18,1%	6,7%	15,6%	6,6%
		CF_{ORC}	25,7%	8,2%	19,5%	9,4%	27,7%	9,6%	22,7%	10,1%	29,3%	10,8%	25,3%	10,7%
	18%	$\eta_{roundtrip}$	72,0%				84,6%				97,2%			
		E_E to HP (GWh/y)	17,0	6,0	14,1	6,2	15,4	5,8	13,5	5,6	14,1	5,6	12,9	5,1
		$E_{E,PV}$ to grid (GWh/y)	0,0	8,3	0,2	8,0	0,0	8,4	0,7	8,6	0,0	8,6	1,4	9,1
		$E_{th,TES}$ (GWh/y)	68,0	23,9	56,3	24,8	72,4	27,3	63,5	26,4	76,1	30,3	69,5	27,7
		$P_{th,TES}$ (MWh)	738,9	303,3	294,9	305,6	792,7	350,3	323,5	332,1	864,0	381,6	346,4	352,6
		CF_{HP}	19,4%	6,8%	16,1%	7,1%	17,6%	6,6%	15,4%	6,4%	16,1%	6,4%	14,7%	5,9%
		CF_{ORC}	28,0%	9,8%	23,1%	10,2%	29,8%	11,2%	26,1%	10,8%	31,3%	12,5%	28,6%	11,4%
	21%	$\eta_{roundtrip}$	84,0%				98,7%				113,4%			
		E_E to HP (GWh/y)	15,5	5,8	13,5	5,6	14,0	5,6	12,8	5,1	12,7	5,4	12,0	4,7
		$E_{E,PV}$ to grid (GWh/y)	0,0	8,4	0,7	8,6	0,0	8,6	1,4	9,2	0,0	8,9	2,2	9,6
		$E_{th,TES}$ (GWh/y)	61,9	23,3	54,1	22,5	65,6	26,3	60,1	23,9	68,6	29,0	65,0	25,1
		$P_{th,TES}$ (MWh)	677,1	298,1	276,3	283,8	752,0	329,5	299,9	304,3	761,9	358,8	331,5	324,8
		CF_{HP}	17,7%	6,6%	15,4%	6,4%	15,9%	6,4%	14,6%	5,8%	14,5%	6,1%	13,7%	5,3%
		CF_{ORC}	29,7%	11,2%	26,0%	10,8%	31,5%	12,6%	28,8%	11,5%	32,9%	13,9%	31,2%	12,0%

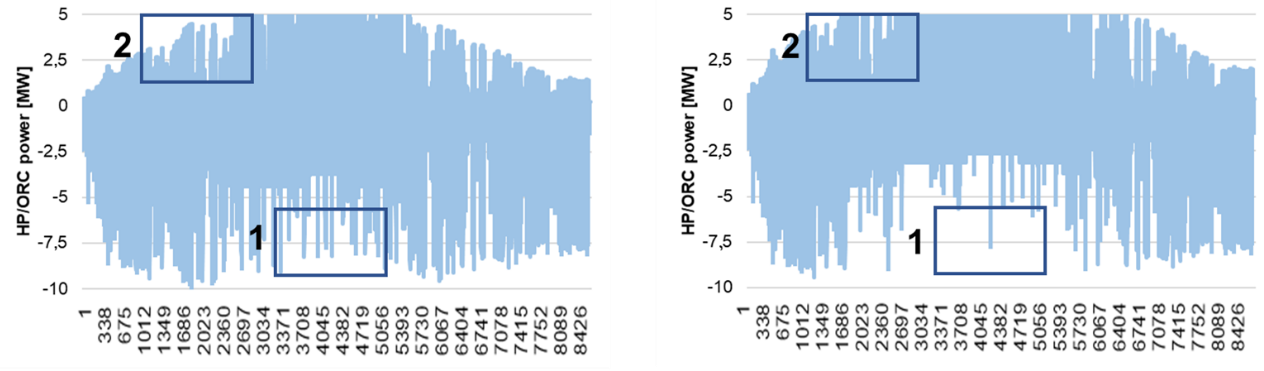

Figure 31 - Effect of the increase of ORC efficiency (left: 15%; right: 21%) on the HP/ORC profile under logic 2

3.2.8. Economic results

This section presents the results of the economic analysis of the CHEST system under the presented logics and in the default operating conditions listed in Table 23. In logic 3, the switch price was set equal to 55 €/MWh.

The results were compared with a business model that was defined taking the cue from a real PHS operating in the North-West of Italy.

Concerning the investment cost of CHEST system vs. PHS, the maturity and readiness of the hydropower plant implies that the CAPEX of this solution is about 21-34 % of the CAPEX of CHEST system, which is less mature and more expensive. Although a strict constraint on the duration of the charging/discharging cycle of the TES was imposed in the model, the size of the TES is still very high: for this reason, this component accounts for 46-66% of the total CAPEX of the CHEST system. As shown in Table 28, the CAPEX for a 5-MW CHEST system spans from 44 to 71 M€ according to the operating logic, which affects the energy balance of TES and, hence, its size.

Variable O&M of the different solutions are computed according to the data agreed with partners and listed in Table 24. Variable O&M consists of the net profit (i.e., revenues minus costs) from the exchange of electric energy with the grid in different configurations.

Under logic 1a ("synchro"), the massive purchase of electric energy from the grid (with a +200% increase of the electric energy price to account for fees, taxes etc.) according to a schedule ruled exclusively by the PHS determines a heavily negative total O&M: the sale of electric energy produced by the ORC cannot counterbalance this expenditure. Thus, this logic is discarded as it cannot guarantee any return of the investment.

In logics 1b, 2 and 3, purchase of electric energy from the grid is avoided thanks to the installation of a dedicated grid-connected PV power plant. Since the revenues from the sale of electric energy produced by ORC and overproduced by the PV plant (572-698 k€) exceed the variable O&M, the total annual O&M costs are positive, i.e., a yearly net profit of 23-467 k€ is ensured. The net profit derived from the operation of the PHS is 248 k€/y.

Although the net profit of the CHEST system exceeds the value of PHS in logic 1b and logic 3, the internal rate of return is higher in case of PHS. However, none of the studied solutions (neither PHS nor CHEST) reaches the investment breakeven during the considered lifetime (30 years) since all the IRR values resulted to be negative. This means that the net profit generated by the operation of the CHEST system did not compensate for the high investment costs of the different components in their expected lifetime. In fact, considering logic 3 for CHEST system (the least negative one with a -6.2% IRR) the amortization of the CAPEX (i.e., the ratio between the CAPEX [€] and the duration of the plant lifetime [years]) is about 3.15 times larger than the net yearly profit. The extremely high CAPEX of the CHEST system (especially due to HP and TES) prevents the investment from being remunerative.

Table 28 - Business model of a 5-MW CHEST system vs. a PHS

Parameter	Unit	Pumped hydro	Logic 1a	Logic 1b	Logic 2	Logic 3
CAPEX						
PV	M€		0,0	0,0	0,0	0,0
HP	M€		18,9	18,9	18,9	18,9
ORC	M€		5,0	5,0	5,0	5,0
TES	M€		47,3	20,7	19,6	20,2
Total CAPEX	M€	15,0	71,2	44,6	43,5	44,1
O&M						
PV	k€/y		0,00	0,00	0,00	0,00
HP	k€/y		-79,16	-29,29	-68,37	-28,81
ORC	k€/y		-128,24	-47,46	-110,76	-46,66
TES	k€/y		-427,47	-158,19	-369,19	-155,55
O&M	k€/y	-225,00	-634,87	-234,94	-548,32	-231,02
Electric energy	k€/y	473,09	-1735,69	670,52	571,57	697,61
Total O&M	k€/y	248,09	-2370,55	435,58	23,25	466,59
Internal Rate of Return		-4,0%	N/A	-6,6%	-17,6%	-6,2%

For this reason, considering logic 3, the business model was replicated introducing the two economic scenarios presented in Table 24. These scenarios reflect the reduction of capital and O&M costs expected for CHEST components in different time lapses in the future.

Variable O&M costs (i.e., the net profit from the exchange of electric energy with the grid) do not change in this supplementary analysis (Table 29). The total net profit increases with the evolution of the CHEST system, i.e. with the decrease of capital costs of different components. In the future scenario, the IRR of the CHEST system almost equals the IRR of the pumped hydro plant.

Therefore, it is concluded that the implementation of the CHEST system cannot be profitable under the assumed boundary conditions and logics, given the high investment costs and the relatively low net profit generated by its operation on the electricity market. Hence, a disrupting and rapid technological development and an increase of the market of these components could reduce the gap with other storage solutions. The participation of CHEST system to the market of ancillary services would provide an extra-profit that might ensure a higher internal rate of return of the investment.

Table 29 - Supplementary business model. Evolution of the market for CHEST system (under logic 3)

Parameter	Unit	Pumped hydro	Current	Future
CAPEX				
PV	M€		0,0	0,0
HP	M€		18,9	13,5
ORC	M€		5,0	4,3
TES	M€		20,2	10,4
Total CAPEX	M€	15,0	44,1	28,1
O&M				
PV	k€/y		0,00	0,00
HP	k€/y		-28,81	-28,81
ORC	k€/y		-46,66	-46,66
TES	k€/y		-155,55	-155,55
O&M	k€/y	-225,00	-231,02	-231,02
Electric energy	k€/y	473,09	697,61	697,61
Total O&M	k€/y	248,09	466,59	466,59
Internal Rate of Return		-4,0%	-6,2%	-4,0%

3.2.9. Possible evolutions

On top of the techno-economic analysis of the CHEST system in default configuration and towards historical time series of electric energy price, a further sensitivity analysis was carried out considering CHEST under operating logic 2. To take into account the strong fluctuations of the electric energy price in Italian and in European market, this section reports the value of the CAPEX ensuring a breakeven at the end of plant lifetime (IRR = 0%, i.e., the amortization of the CAPEX and the annual O&M and operating costs are counterbalanced by the sale of electric energy to the grid). Logic 2 was chosen instead of Logic 3 in order not to introduce a further variable (the switch price) in the sensitivity analysis, although Logic 3 has been proven to be the most economically efficient.

Table 30 - CAPEX (M€) of 5/10-MW CHEST in current and future scenarios

		HP COP		
		4	**4,7**	**5,4**
ORC efficiency	**15%**	35,0 - 22,5	39,5 - 25,3	43,5 - 27,8
	18%	34,2 - 22,1	38,1 - 24,6	41,7 - 26,9
	21%	33,2 - 21,6	36,9 - 23,9	41,0 - 26,5

Table 30 reports the values of the investment cost (in million €) expected for a 5/10-MW (ORC/HP) CHEST system under different technical assumptions: COP varying between 4 and 5,4 and ORC efficiency spanning from 15 to 21%. Costs are also assessed considering two different economic scenarios for each COP/efficiency combination (Table 24): the current market scenario is associated with the first, higher value; the future market scenario implies a dramatic reduction of investment cost. The reader should take into account that O&M costs do not vary between the two scenarios due to assumptions done so far (Table 24).

These expected investment costs can be compared with Table 31, which reports the values that the investment cost should assume in order to ensure IRR = 0% (i.e., breakeven at the end of plant lifetime). This analysis was carried out considering a variation of the average electric energy price between 50 and 500 €/MWh, respectively the base value recorded for several years before Covid-19 pandemics and the peak value reached in many EU countries after February 2022 (Russian invasion of Ukraine). Of course, a weak performance of the CHEST system (low values of HP COP and ORC efficiency) would not be paid back even by a very profitable sale of electric energy to the grid.

For instance, in case of ORC efficiency equal to 15%, the red values highlight that the “breakeven CAPEX” in such configurations are even lower than the investment cost estimated in future market scenario, hence revealing that it might be difficult for CHEST system to be profitable and competitive even in a future market scenario.

Only in case of high day-ahead electricity market price, the “breakeven CAPEX” (e.g., 37,5 M€ for HP COP = 5,4) would be intermediate between the current and future costs (43,5 - 27,8 M€): in this configuration, CHEST operation might be profitable providing a slightly positive IRR due to very high price of electric energy sold to the grid that counterbalances and overshoots the costs (CAPEX and OPEX), as highlighted by the yellow values. The reduction of CAPEX from current market value needed in this configuration (HP COP: 5.4; ORC efficiency: 15%; EE avg. price: 500 €/MWh) to reach IRR = 0% is around (37,5-43,5)/43,5 = 14% (cf. Table 30 and Table 31).

Table 31 – CAPEX (M€) associated to IRR = 0, with variations of technical parameters and avg. EE price (logic 2)

			HP COP		
			4	**4,7**	**5,4**
		EE avg. price (€/MWh)			
ORC efficiency	**15,0%**	**50**	N/A	N/A	0,6
		100	2,3	3,2	4,7
		200	8,4	10,4	12,9
		350	17,5	21,1	25,2
		500	26,6	31,8	37,5
	18,0%	**50**	1,5	2,8	4,2
		100	5,1	7,1	9,1
		200	12,4	15,7	18,9
		350	23,4	28,6	33,6
		500	34,3	41,4	48,3
	21,0%	**50**	4,1	5,9	7,6
		100	8,4	10,9	13,3
		200	16,9	20,8	24,7
		350	29,7	35,7	41,7
		500	42,4	50,7	58,8

One can notice that the "yellow region" (i.e., the combinations of technical and economic parameters that make CHEST system profitable in current-to-future scenario) spreads as the performance of CHEST system improves. At last, in the most efficient configurations studied, the "breakeven CAPEX" becomes even higher than the investment cost in the current market scenario (e.g., 41,7 vs. 41,0 M€ in case of HP COP = 5,4 and ORC efficiency = 21%), highlighting that CHEST would be profitable in such techno-economic configuration even today, considering the current specific cost of the major components.

This analysis highlights the strict correlation between the trend of energy market and technology with the profitability of the CHEST system: the extremely high investment costs represent a barrier to the widespread diffusion of such P2P system in a short term. However, future evolutions and possible subsidies may accelerate the application of CHEST systems in Europe, in particular in areas where other storage solutions cannot be properly installed and operated due to several reasons.

3.3. CHEST as an alternative to DSO investment for grid reinforcement

The widespread and unavoidable diffusion 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. For instance, in Italy, in the next years a growing amount of energy will be dispatched from the wind and solar power plants installed in the South towards the more energy-demanding regions of the Northern area of the peninsula.

The electric grids will face a radical and brave 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 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 manage properly such amounts of energy, solutions for the storage, conversion and time-shift of renewable energy are available as well. Operating as a “stop-and-go” backup reservoir, these devices may store the surplus energy production from renewable plants in order to keep the balance between energy demand and supply, avoiding the curtailment of this renewable overproduction. When variable (i.e., non-schedulable) renewable plants do not operate and the load exceeds the energy production, storages are discharged.

Acting as Power-to-Heat-to-Power system, CHEST system may accomplish this task avoiding the need for DSO/TSO to reinforce the grid, if such storage backup solutions are installed in critical sections, i.e., where clusters of renewable plants are present and bottlenecks in the electric energy dispatchment are present.

The business model in this section aims to compare techno-economic viability of installing and operating a CHEST system as a “stop-and-go” (time-shift) solution serving a new large-size renewable power plant. The results of the business model were compared with the alternative solution of reinforcing a certain portion of the distribution grid (i.e., the branch connecting the power plant to both the transmission grid and the local consumption nodes).

3.3.1. Technical data and assumptions

An arbitrary location in the South of Italy (Apulia region, Figure 32) was chosen to download the irradiance data from PVGIS platform and simulate the production profile of the PV plant.

Figure 32 - Location of PV plant and CHEST system

The PV plant has a nominal power of 5-100 MW.

The HP/ORC ratio is set equal to 2, as an average value of this parameter that can be fully representative of all the possible working configurations, as outlined in Deliverable 6.5. This value is strongly affected by the operating rationale set for the CHEST system in this business model, that is explained later in this section: hence, 2 is the minimum considered value.

A sensitivity analysis on the following performance indexes was carried out:

- COP (Coefficient of Performance) of HP spans from 4 to 5,4, with the latter value corresponding to a temperature of the heat source of 80 °C, based on the performance map of the HT-HP for butene (see CHESTER deliverable D2.1);
- the efficiency of the ORC (Organic Rankine Cycle) engine spans from 15 to 21%. The lower value was derived from the CHESTER deliverable D2.1, based on the performance map of the ORC for butene, assuming condensation to the environment.

The adopted operating rationale is the Logic 2 – RES-driven of the previous business model (Section 3.2.2). The rationale adopted to size of the components is explained later. The operation of the CHEST system is totally ruled by the availability of energy from the dedicated PV plant. Charging phase: HP operates when RES is available from the dedicated plant. Discharging phase: ORC switches on when the PV plant is not operating. The ORC power is modulated in order to close the energy balance of the thermal energy storage (TES) on a daily scale, i.e. thermal energy generated by the heat pump and stored in TES equals the amount of thermal energy sent to the ORC on any day of the year.

Since the timescale of the thermal energy storage (TES) is assumed to be below 24 hours (i.e., the multi-daily or seasonal operation is excluded, as in the previous business case), thermal losses through the TES walls are neglected. The size of the high-T TES was also varied depending on the simulated scenario.

Furthermore, as a second constraint of the simulation, the power at which the HP and ORC operate is clearly kept below their nominal values and excess production from the dedicated PV plant is sold to the grid.

The grid to which the PV plant is connected is not unconstrained. To simulate the unsuitability of the existing grid to dispatch the extra-energy produced by the newly installed PV plant, a flat threshold value of the dispatching capacity was introduced during sunlight hours: this value is expressed as a percentage of the size of the new PV plant.

This value clearly depends on the demand-production mismatch and difference; so, in real operation, rather than being flat, it would vary:

- along a day, due to day/night differences in production profile mainly;
- throughout the year due to seasonal variation of demand and production profiles.

As a reasonable preliminary assumption to simplify this business model, the flat value was considered as a weighted average of such variations. Hence, a sensitivity analysis was carried out: the limit dispatching capacity of the grid was set equal to 5, 10, 20, 40, 80% of the PV nominal power. As an example, in the case of a 100 MW PV plant, an average threshold value of dispatching capacity equal to 10% means that the grid can only dispatch up to 10 MWh in one hour: this means that the grid is highly congested or that the tension level is no more adequate. The following graph summarizes the operating logic, where the residual curtailment at peak production hours clearly depends on the spread between the PV production and the available capacity of HP, which is limited by the two aforementioned constraints.

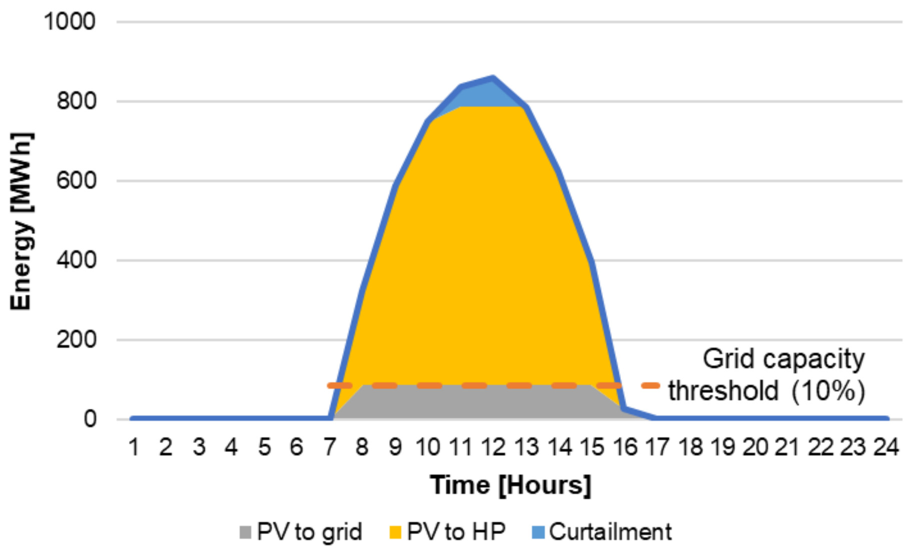

Figure 33 - Logic for the dispatchment of electric energy from the PV plant

To make the analysis independent from the choice of the geographical location for the RES plant (i.e., releasing the analysis from the knowledge of grid topology), a parametric analysis was set up (Figure 34).

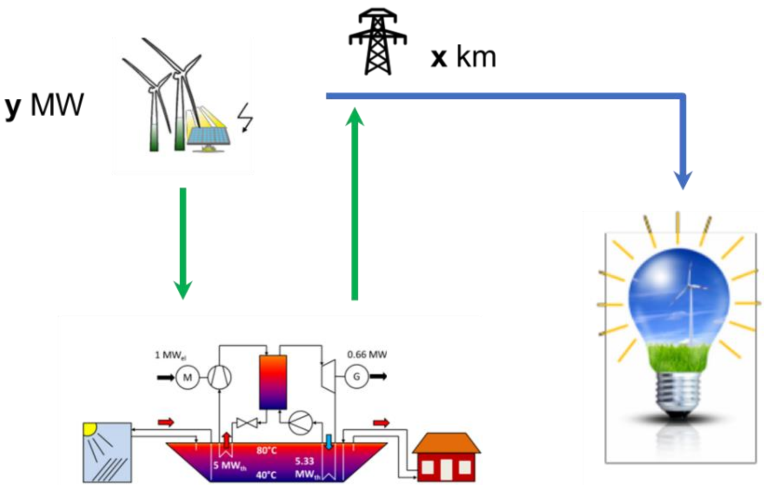

Figure 34 - Rationale of the parametric business model

The research question of this business case can be summarized as follows. Provided a newly installed RES plant of **y** MW connected to a distribution line with a certain dispatching limit (5-80% of the newly installed PV capacity), what is the total investment cost (capital and O&M costs) to develop

- an on-site Power-to-Power CHEST system vs.
- a new distribution line,

in order to avoid the curtailment of PV energy? Since the cost of a new distribution line strictly depends on its length, which is the **x** grid length associated with the breakeven of the two solutions? Referring to Figure 33, notice that, in lack of one of the two mentioned interventions, the share of curtailed energy would also include the yellow area (marked as "PV to HP" in the figure).

Table 32 summarizes the technical data and operating assumptions introduced to carry out the analysis. The size of the CHEST HP is equal to the residual un-dispatchable power (curtailed, otherwise) produced by the PV plant; e.g., in case of a 50 MW PV plant connected to a 80%-limited distribution grid (i.e., 40 MW), the size of HP would be 10 MW.

As a further remark, a waste heat supply at a temperature consistent with CHEST HP operation is assumed to be available for free on CHEST site: the system is assumed to be thermally integrated at the heat pump side and able to discharge to ambient temperature.

Table 32 - Technical data and assumptions for the simulation of DSO new investment vs. CHEST operation

Parameter	Value	Unit	Notes
Min. HP-ORC capacity ratio	2		
Size of the PV plant	50	MW	Varied between 5 and 100 MW
Dispatching capacity of the grid	80%		Varied between 5 and 80%
Nominal size of the HP in CHEST		MW	Equal to non-dispatchable PV power
COP of HP	5,4	-	Varied between 4 and 5,4
Thermal losses of TES	negl.		
Efficiency of ORC	15%		Varied between 15 and 21%

3.3.2. Economic scenarios and financial parameters

In all the simulations, local electricity prices valid in 2019 in the “South-Italy” zone of the Italian Power Exchange were applied. These prices consisted of the hourly market prices. The profiles after 2020 were not considered due to significant variations caused by COVID-19 pandemics. The effect of having higher electricity prices (50-500 €/MWh) has been analyzed separately as sensitivity analysis (see section 3.3.7)

Concerning the costs for the reinforcement of one km of distribution line (including cables and transformers), two scenarios were introduced [2-4]:

- scenario 1 – low-cost. Capital cost: 60000 €/km; O&M dispatching cost: 5 €/MWh;
- scenario 2 – high-cost. Capital cost: 120000 €/km; O&M dispatching cost: 10 €/MWh.

For what concerns the costs of CHEST system, PV plant and other assumptions, please refer to the section “Economic scenarios and financial parameters” of the previous business case, in particular to Table 24.

3.3.3. Key techno-economic performance indicators

Please, refer to the section “Key techno-economic performance indicators” of the previous business case.

3.3.4. Results of the simulations

This section presents the results of the simulations run with a CHEST system coupled with a PV plant of 50 MW and connected to a distribution line with a dispatching threshold of 40 MWh (80 % of the PV size).

Since the CHEST operation is solely ruled by the productivity of the dedicated PV plant, this solution may be adopted for time-shift of the energy produced by the oversized grid-connected RES plant: during sunlight hours, the energy overproduction of the PV plant (i.e., the share that would be otherwise curtailed) is used to run the HP. Heat stored is then used in the evaporator of the ORC at night to generate electric energy that is sold to the grid.

Figures hereunder summarize in a graphical way the HP/ORC profile of the CHEST system and the operation (i.e., charging/discharging) of the TES on an annual basis. A detail about the differences between wintertime and summertime is reported as well. As a straightforward consequence of the mission to be accomplished and of the operating logic adopted, CHEST system is expected to operate in a more frequent way during summertime, when higher energy fluxes from the PV plant cannot be fully dispatched by the grid. The magnitude of the grid bottleneck (i.e., where the orange dashed line in Figure 33 is positioned) directly affects the switch-on and -off events of the CHEST system and the power rate of the HP/ORC components. In the case of an 80%-capacity grid, the curtailment events are rare and of limited magnitude. As discussed during the sensitivity analysis in the next sections, a heavier limitation of the capacity of the grid to dispatch would imply a major role of the CHEST system in the correct management of the energy fluxes.

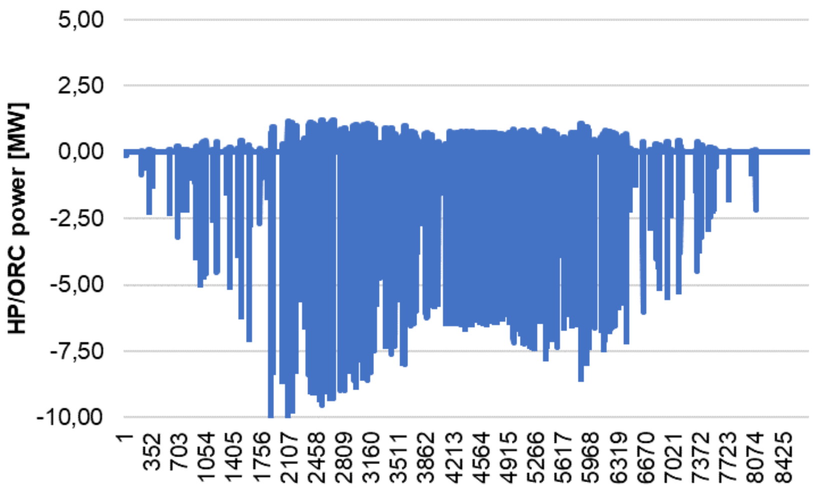

Figure 35 - HP/ORC operating profile of CHEST system

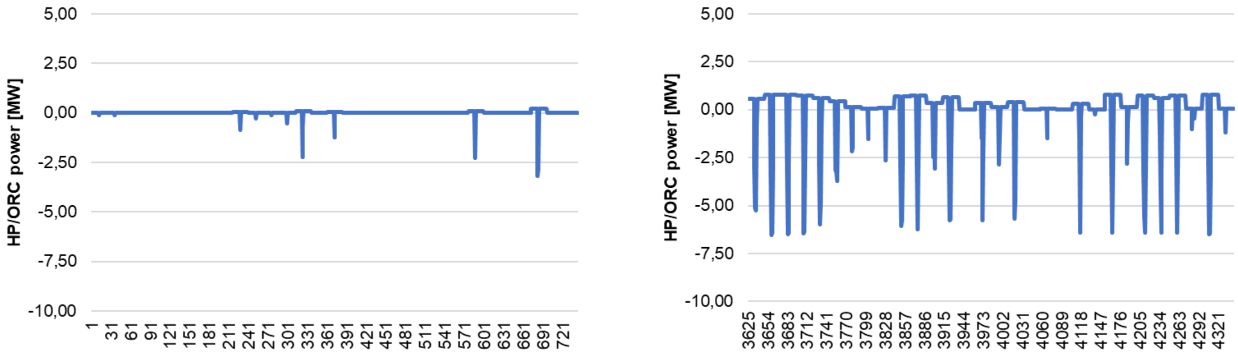

Figure 36 - HP/ORC operating profile of CHEST system (left: January; right: June)

The constraint on the duration of the TES charge/discharge cycle (24 hours) allowed it to keep its size as low as possible, hence reducing its impact on the total investment cost.

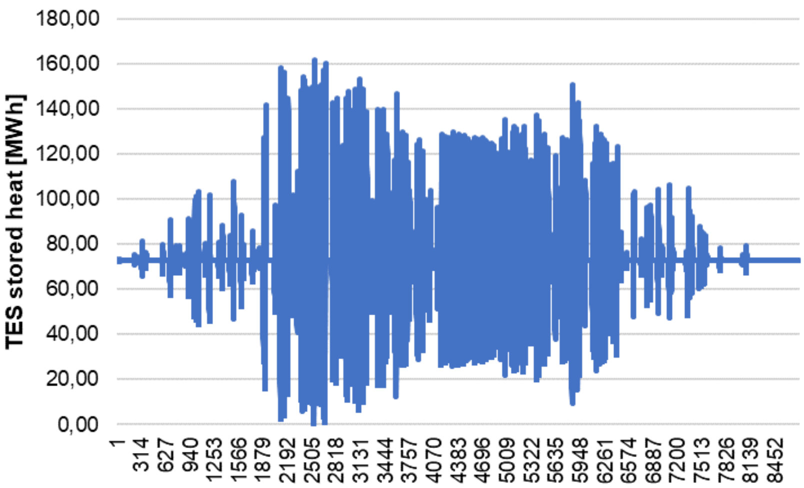

Figure 37 - TES charge/discharge profile

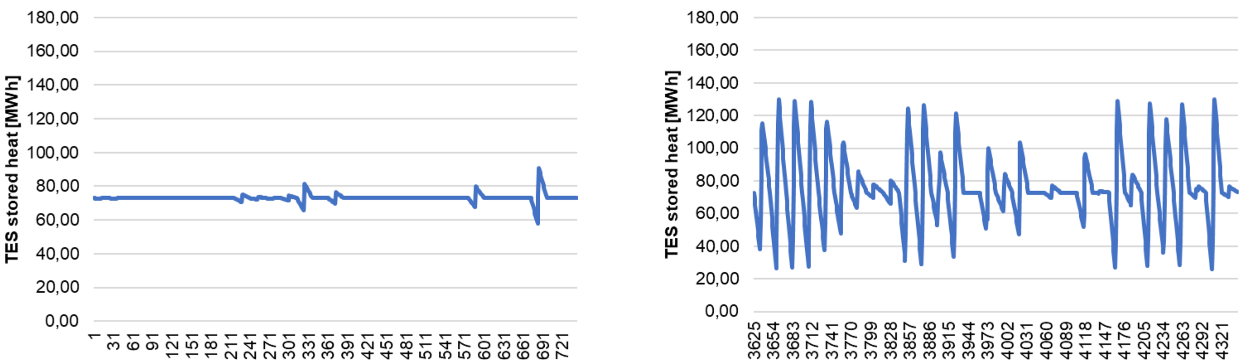

Figure 38 - TES charge/discharge profile (left: January; right: June)

Table 33 summarizes the technical performance indicators of the CHEST system in the default values configuration (Table 32). Notice that in this configuration, only 3% of the PV production (about 2,71 GWh/y) would be curtailed and, to avoid it, this overproduction is used to run the heat pump. In fact, the HP is characterized by a very low capacity factor.

Table 33 - Technical output of the simulations of CHEST system

Parameter	Unit	
$E_{E,in}$	GWh/y	2,71
$E_{E,out}$	GWh/y	2,19
$E_{E,in,PV}$	GWh/y	2,71
$E_{E,PV,grid}$	GWh/y	86,99
$E_{E,PV,curt}$	GWh/y	0,00
$E_{th,TES}$	GWh/y	17,42
$P_{th,TES}$	MWh	162
$\eta_{roundtrip}$	%	81,0%
CF_{HP}	%	3,09%
CF_{ORC}	%	20,62%

3.3.5. Sensitivity analysis: the effect of grid constraints

The following analysis highlights the effect of the grid congestion on the P2P task of the CHEST system. As Figure 39 shows, the reduced presence of bottlenecks on the distribution grid limits the rate of power and the total amount of energy exchanged by CHEST. When the grid experiences massive limitations on the amount of energy that can be dispatched without any issue, CHEST system may play a pivotal role in the correct management of energy fluxes, relieving the grid of congestion when non-schedulable renewable plants work at maximum power.

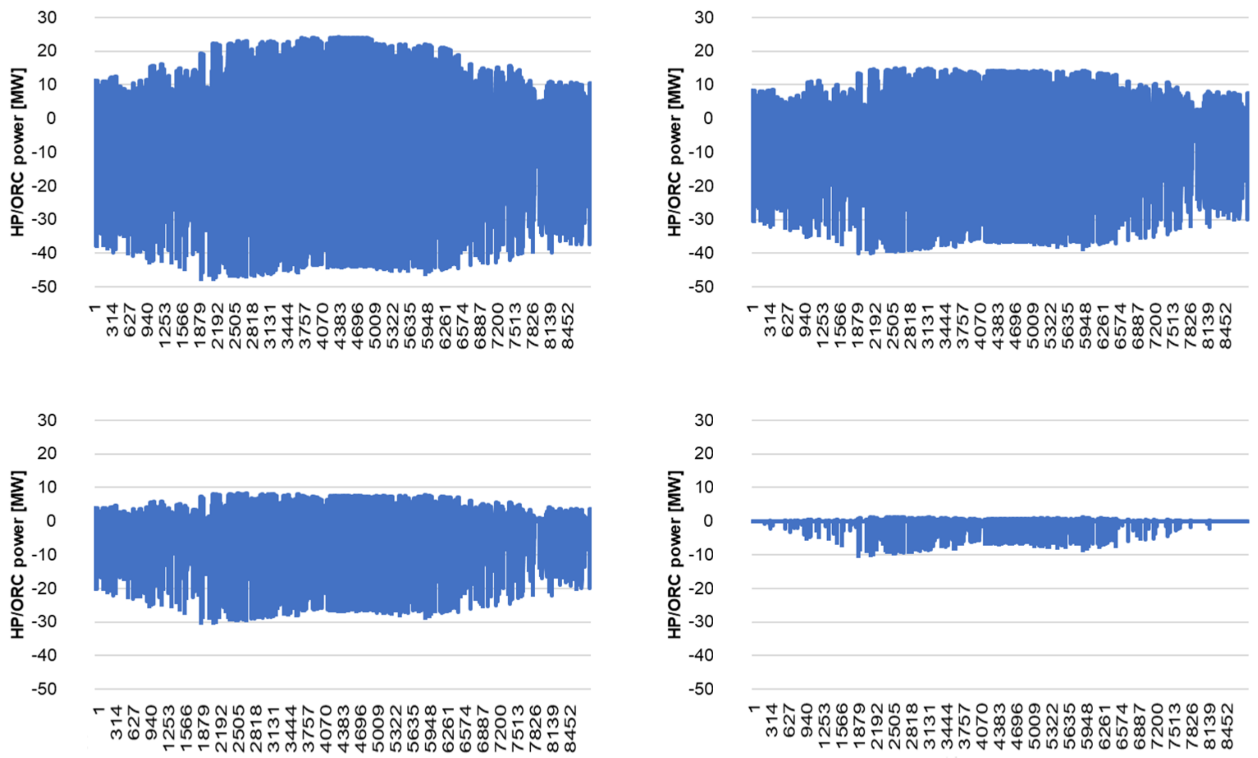

Figure 39 - HP/ORC operating profile of CHEST system. Grid capacity threshold: 5% (top left); 20% (top right); 40% (bottom left); 80% (bottom right)

Of course, the CHEST system is asked to support the grid whenever some criticalities arise, hence, in particular, during summertime (Figure 40), when PV power plants (like the simulated one in this business model) reach their maximum productivity. Notice that the power rate of ORC in June almost doubles the ORC power rate registered in January, since more energy is available (and should be time-shifted) in summertime.

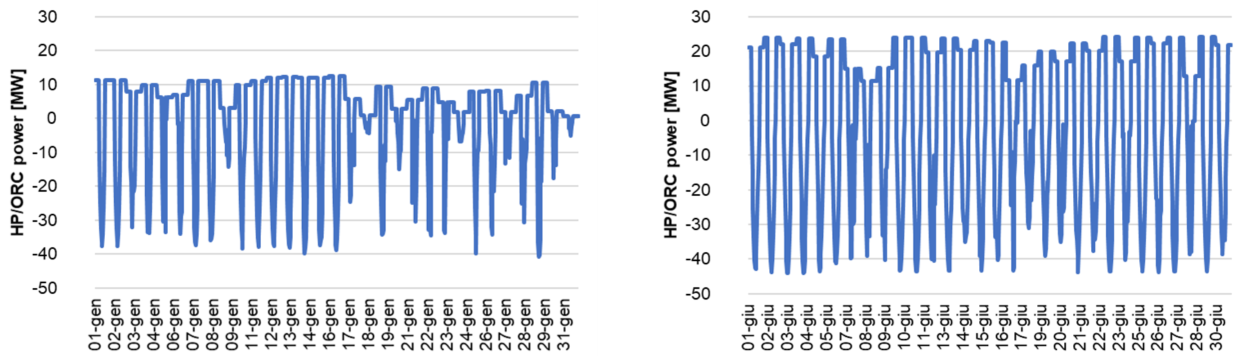

Figure 40 - HP/ORC operating profile of CHEST system (left: January; right: June). Grid capacity threshold: 5%

As a consequence of this increased magnitude of the electric energy fluxes exchanged by CHEST system, also the amount of thermal energy rises proportionally. Hence, a higher capacity of TES is needed when the distribution grid is particularly congested or, anyway, not adequate to dispatch high amounts of electric energy.

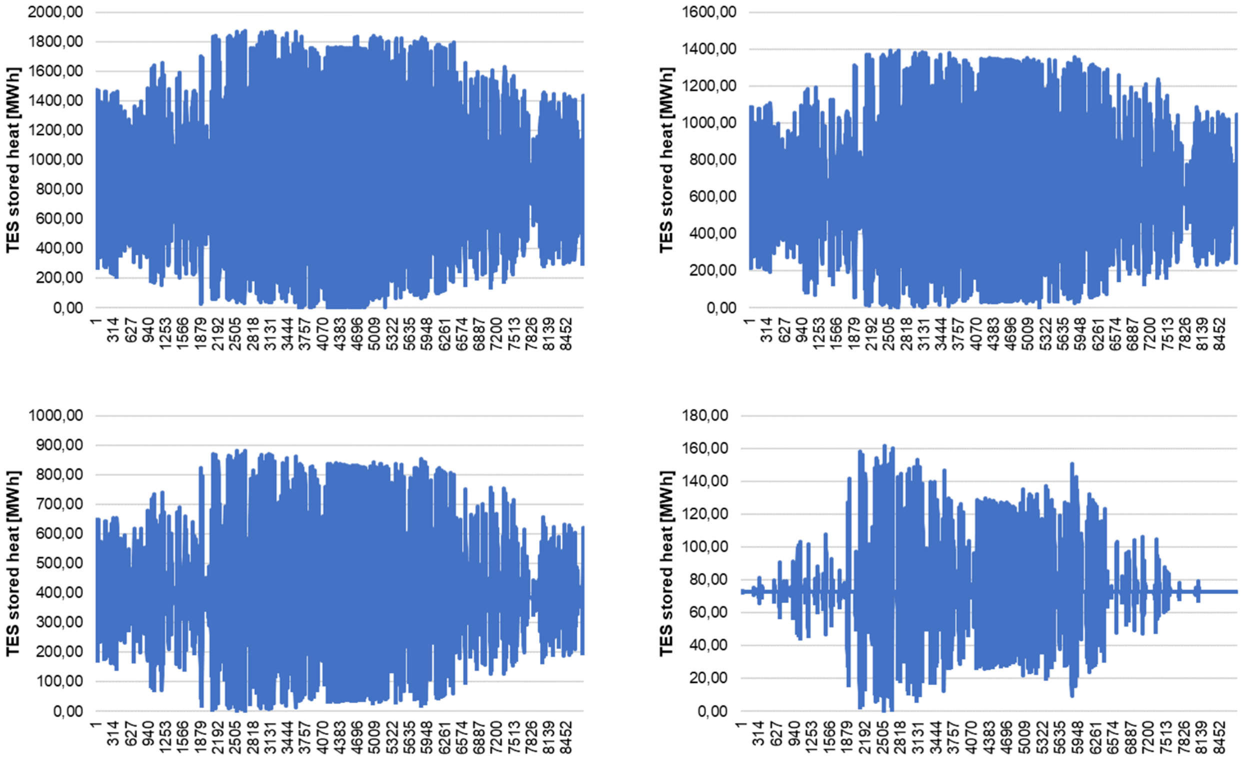

Figure 41 - TES charge/discharge profile. Grid capacity threshold: 5% (top left); 20% (top right); 40% (bottom left); 80% (bottom right)

This is evident in Figure 41: the size of TES is kept very low (cf. days in Figure 42 with very low charging level) when electric energy can be directly injected in the grid and bypasses CHEST system. When the grid is somehow critical, although the charge/discharge cycle is kept under 24 hours, the size of TES increases, as well as the rate of charge/discharge of the storage. This has clear consequences on the system costs.

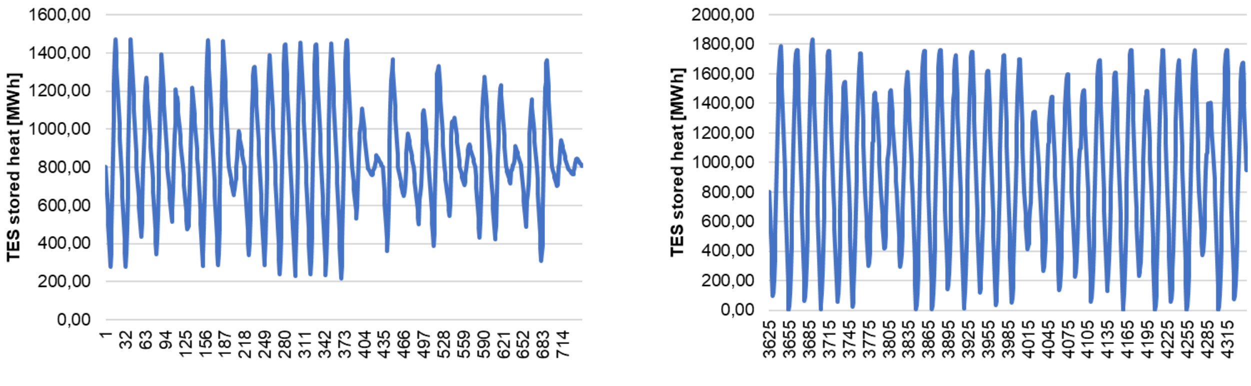

Figure 42 – TES charge/discharge profile (left: January; right: June). Grid capacity threshold: 5%

The effect on technical KPIs of variations of the system efficiency was analyzed. In particular, the analysis focused on the variation of the HP Coefficient of Performance (COP) between 4 and 5,4 and of the efficiency of ORC between 15 and 21%.

Keeping the constraints and limitations about the power rate and the energy balance of the TES and considering the default size of the PV plant (50 MW), Table 34 summarizes the results of the sensitivity analysis towards different grid dispatching thresholds.

The increase of the efficiencies of the two components implies a rise of roundtrip efficiency, since intermediate losses of TES are neglected due to its daily timescale. In reference case (Table 32), roundtrip efficiency equals 81% (Table 33).

A higher COP of the HP has the double effect of:

- reducing the withdrawal of the electric energy produced by the PV plant to run the HP (hence increasing the share of electric energy that is curtailed; notice that the amount that is regularly injected in the grid is a constant value that depends on the dispatching threshold);
- increasing the thermal energy available in the TES. However, the aforementioned constraints avoid the uncontrolled increase of the thermal level of the TES, limiting the growing discharge rate to feed the ORC evaporator: to save the energy balance, also the incoming heat is capped, limiting the HP power rate.

For these reasons, thermal energy that is totally exchanged by TES increases when COP increases. As well, it increases when the grid is more critical, and bottlenecks are relieved by Power-to-Heat-to-Power operation of the CHEST system. As well, higher charge/discharge rates increase the size [MWh] of the TES.

A higher efficiency of the ORC has the double effect of:

- reducing the amount of thermal energy supplied by the TES to the ORC evaporator on those days when the ORC works at or close to its nominal power. Since less heat should be supplied to TES in order to close the daily balance, in this period the HP can operate at partial load, hence increasing the share of PV energy that is curtailed;
- increasing the power output of ORC on days when it operates at partial load. In this situation, heat demand to TES may be constant or even decrease according to the variation in the ORC power output. In any case, the power rate of HP does not increase.

For these reasons, the size and the energy exchanged by the TES decrease.

The remarks and comments about the effect of the grid dispatching capacity on the HP/ORC operation of CHEST system and the role of TES are confirmed in the following table (cf. Figure 39 and Figure 41).

Table 34 - Sensitivity analysis. Effect of system efficiency on the technical KPIs

		HP COP														
		4					4,7					5,4				
	Grid capacity →	**5%**	**10%**	**20%**	**40%**	**80%**	**5%**	**10%**	**20%**	**40%**	**80%**	**5%**	**10%**	**20%**	**40%**	**80%**
ORC efficiency 15%	η_{rt}			60.0%					70.5%					81.0%		
	$E_{E,in}$ (GWh/y)	79,6	70,7	55,2	30,4	2,7	79,6	70,7	55,2	30,4	2,7	79,5	70,7	55,2	30,4	2,7
	$E_{E,PV,grid}$ (GWh/y)	10,1	19,0	34,5	59,3	87,0	10,1	19,0	34,5	59,3	87,0	10,1	19,0	34,5	59,3	87,0
	$E_{E,PV,curt}$ (GWh/y)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,06	0,00	0,00	0,00	0,00
	$E_{th,TES}$ (GWh/y)	569,2	500,7	369,0	185,0	12,9	668,8	588,3	433,6	217,3	15,2	768	676	498	250	17
	$P_{th,TES}$ (MWh)	1396,1	1281,8	1031,1	653,4	120,0	1640,5	1506,1	1211,6	767,8	141,0	1874	1730	1392	882	162
	CF_{HP}	19,1%	17,9%	15,8%	11,6%	3,1%	19,1%	17,9%	15,8%	11,6%	3,1%	19,1%	17,9%	15,8%	11,6%	3,1%
	CF_{ORC}	30,2%	31,2%	34,2%	34,0%	20,6%	30,2%	31,2%	34,2%	34,0%	20,6%	31,0%	31,2%	34,2%	34,0%	20,6%
18%	η_{rt}			72.0%					84.6%					97.2%		
	$E_{E,in}$ (GWh/y)	79,6	70,7	55,2	30,4	2,7	79,1	70,7	55,2	30,4	2,7	75,8	69,5	55,2	30,4	2,7
	$E_{E,PV,grid}$ (GWh/y)	10,1	19,0	34,5	59,3	87,0	10,1	19,0	34,5	59,3	87,0	10,1	19,0	34,5	59,3	87,0
	$E_{E,PV,curt}$ (GWh/y)	0,00	0,00	0,00	0,00	0,00	0,26	0,00	0,00	0,00	0,00	1,91	0,62	0,00	0,00	0,00
	$E_{th,TES}$ (GWh/y)	569,2	500,7	369,0	185,0	12,9	667,3	588,3	433,6	217,3	15,2	752	669	498	250	17
	$P_{th,TES}$ (MWh)	1396,1	1281,8	1031,1	653,4	120,0	1621,7	1506,1	1211,6	767,8	141,0	1793	1685	1392	882	162
	CF_{HP}	19,1%	17,9%	15,8%	11,6%	3,1%	19,0%	17,9%	15,8%	11,6%	3,1%	18,2%	17,6%	15,8%	11,6%	3,1%
	CF_{ORC}	30,2%	31,2%	34,2%	34,0%	20,6%	32,2%	31,2%	34,2%	34,0%	20,6%	35,4%	34,3%	34,2%	34,0%	20,6%
21%	η_{rt}			84.0%					98.7%					113.4%		
	$E_{E,in}$ (GWh/y)	79,2	70,7	55,2	30,4	2,7	75,3	69,2	55,2	30,4	2,7	70,7	65,7	55,1	30,4	2,7
	$E_{E,PV,grid}$ (GWh/y)	10,1	19,0	34,5	59,3	87,0	10,1	19,0	34,5	59,3	87,0	10,1	19,0	34,5	59,3	87,0
	$E_{E,PV,curt}$ (GWh/y)	0,22	0,00	0,00	0,00	0,00	2,15	0,77	0,00	0,00	0,00	4,36	2,35	0,04	0,00	0,00
	$E_{th,TES}$ (GWh/y)	568	501	369	185	13	653	581	434	217	15	729	651	498	250	17
	$P_{th,TES}$ (MWh)	1383	1282	1031	653	120	1556	1462	1212	768	141	1698	1615	1372	882	162
	CF_{HP}	19,0%	17,9%	15,8%	11,6%	3,1%	18,1%	17,5%	15,8%	11,6%	3,1%	17,0%	16,7%	15,7%	11,6%	3,1%
	CF_{ORC}	32,0%	31,2%	34,2%	34,0%	20,6%	35,7%	34,6%	34,2%	34,0%	20,6%	38,6%	37,8%	35,7%	34,0%	20,6%

3.3.6. Economic results

This section presents the economic results of the base case study (50 MW PV plant connected to an 80%-uncongested grid) following the same procedure as in the previous business model. The two scenarios for CHEST system refer to Table 24, while the two scenarios for grid reinforcement are described in section 3.3.2.

As shown in the table, the high costs of CHEST components represent an important penalty for the CAPEX of the system. Since the HP/ORC power rate and the amount of heat exchanged by the TES increase at lower grid dispatching capacity (i.e., when CHEST system is more invoked to solve issues and bottlenecks on the grid), also their relative weight on the total CAPEX increases. As the sensitivity analysis will highlight, this represents an important barrier to the economic feasibility of the CHEST system and, hence, to the competitiveness with the alternative option of reinforcing the existing electric grid.

Table 35 - Business model of a CHEST system serving a 50-MW PV plant vs. grid reinforcement. Evolution of the market

Parameter	Unit	Current	Future	Grid - 1	Grid - 2
CAPEX					
HP	M€	18,9	13,5		
ORC	M€	1,2	1,0		
TES	M€	8,3	4,3		
Total CAPEX	M€	28,5	18,8	26,8	23,2
OPEX					
HP	k€/y	-13,5	-13,5		
ORC	k€/y	-21,9	-21,9		
TES	k€/y	-87,1	0,0		
Fixed O&M	k€/y	-122,6	-35,5	-13,5	-27,1
Variable O&M	k€/y	113,1	113,1	122,8	122,8
Total O&M	k€/y	-9,5	77,6	109,2	95,7
Breakeven distance	km			447	193
Internal Rate of Return		**N/A**	**-10,3%**	**-10,3%**	**-10,3%**

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. In the reference case study in Table 35, a 34% reduction is expected.

Despite this, the sale to the grid of the electric energy produced by CHEST ORC ensures a limited net profit that may even not counterbalance the high fixed operating and maintenance costs of the system. The difference of variable O&M costs between CHEST and the grid reinforcement scenario is due to the additional costs for the dispatch of extra-energy with respect to the current congested grid.

In the reference case study, the IRR of the investment for a PtP CHEST system serving a 50-MW PV plant is strongly negative, if current day-ahead electric energy price is considered. As mentioned, the investment for the reinforcement of the existing electric grid strictly depends on the length of the grid. In order to keep the comparative analysis geographically independent, the grid length ensuring the breakeven between the two options is estimated. This length was assessed considering the two different scenarios for the grid reinforcement options. The comparative analysis was performed with the future market scenario for CHEST system. The resulting length of the line that includes the new node of the 50-MW PV plant and that connects it to the electric transmission grid and to the end users should be about 450 km in the cheapest scenario (scenario 1) for grid reinforcement (i.e., if the distance is shorter, grid reinforcement is economically more viable than CHEST). Assuming the increase of grid investment and operation costs from scenario 1 to scenario 2 reported in the section 3.3.2, the breakeven length of the congested line is around 190 km. It is evident that it might be difficult for the CHEST system, even in future market scenario (cf. Table 24), to compete with the alternative of grid reinforcement in the reference case study (i.e., when the installed power of the PV plant is significant, like 50 MW in this configuration). In this situation, even if the grid is not so congested, a retrofitting intervention to reinforce the existing grid and increase the amount of energy that can be dispatched is more rewarding: it is unrealistic that the installation of a 50-MW PV plant would impact on such extended grid sections. The interventions would be limited to shorter lines, hence making the grid reinforcement more rewarding than the installation of a 10/5-MW (HP/ORC) CHEST system.

3.3.7. Results for different electricity prices

As a final step of the business model, the aforementioned KPIs (the internal rate of return of the investment for a CHEST system in current and future market scenarios and the grid length ensuring the cost breakeven with the grid reinforcement under grid scenario 2) were assessed against mutual variations of the day-ahead electricity price and the grid dispatching threshold.

Table 36 - Variation of the IRR and of breakeven length with the day-ahead electricity price and the grid dispatching threshold. Size of PV plant: 5 MW

Size of PV plant (MW)	EE avg. Price (€/MWh)	KPI	Dispatching capacity of the grid [% of PV size] (the lower % the more congested power grid) Future market scenario				
			5%	**10%**	**20%**	**40%**	**80%**
5	**50**	**IRR**	-3,8%	-4,0%	-4,4%	-5,5%	-10,3%
		Length X (km)	143	132	110	75	19
	100	**IRR**	-2,4%	-2,7%	-3,1%	-4,4%	-9,9%
		Length X (km)	138	128	107	73	19
	200	**IRR**	-0,3%	-0,6%	-1,2%	-2,6%	-9,1%
		Length X (km)	133	124	103	70	18
	350	**IRR**	2,2%	1,8%	1,2%	-0,6%	-8,1%
		Length X (km)	129	120	100	69	17
	500	**IRR**	4,4%	3,9%	3,1%	1,1%	-7,3%
		Length X (km)	128	118	99	67	16

Table 36 reports the results of the sensitivity analysis, keeping the size of the PV plant equal to 5 MW. Since the distribution function of the PV energy production is not linear and the HP/ORC profile does not vary proportionally with the grid dispatching threshold (cf. Figure 39), the size of CHEST components and their power rate does not vary linearly with these parameters, as well as the amount of exchanged thermal/electric energy. The resulting investment and O&M costs (the latter also includes the profit from the sale of electric energy produced by ORC and delivered to the grid) do not vary proportionally with the grid dispatching capacity.

As a macrotrend, Table 36 highlights that the increase of grid congestion, i.e., the reduction of dispatching capacity from 80% to 5%, implies an increase of IRR. This is because the cumulative profit from the sale of power (from ORC generation) to the electric grid is higher and, in case of positive IRR, counterbalances the increased investment cost for a bigger CHEST system.

Another interesting element is the breakeven length in different configurations. The reader should bear in mind that length X is directly proportional to the PV size, assumed the same day-ahead market price and grid dispatching capacity (e.g., for a 50-MW PV plant, i.e., 10 times larger than in Table 36, connected to a 5-% dispatching grid and in a 200-€/MWh scenario, IRR and the breakeven length would be -0,3% and 1330 km, respectively). While the breakeven with the grid reinforcement option seems to be difficult in case of larger PV plants (it is unrealistic that such length of reinforcement lines would be built, so CHEST cannot compete here), CHEST system starts to be more interesting if coupled with PV plants characterized by small sizes (≤ 10 MW). In case of distribution lines that are not affected by heavy dispatching limitations (40-80% of threshold value), the breakeven length reduces to less than 100 km. Notice that positive IRR values are reached in future market scenario, when the PV plant is connected to a grid with heavy limitations and in market scenarios with higher day-ahead market price: in this case, the installation costs are more than counterbalanced by the profit from energy sale and energy curtailments (especially during summertime) are avoided. The breakeven values of the grid length to be reinforced span from about 70 to 130 km.

Considering the future market scenario for CHEST, this result is particularly interesting for the energy systems with a higher penetration of distributed small-size non-schedulable renewable energy plants. In particular, the installation of a CHEST system as a support device for the time-shift of electric energy that would be otherwise curtailed has a great potential in areas that are not close to the transmission grid: to avoid curtailment due to dispatching limitations, CHEST systems could relieve the grid of the congestions and bottlenecks in a profitable way.

4. Conclusions

The CHEST system is likely to suit services on the future balancing energy markets and this given its 15-minutes minimal response time particularly in Replacement Reserve (RR) and Imbalance services (IN), and to some extent also in mFRR. From an economical point of view CHEST has currently significantly higher costs than other technologies. The cost of the CHEST plant is expected to gradually reduce over the years as the HP and ORC components should get integrated and cost of the latent storage built of PCM materials will potentially halve. Moreover, the CHEST system has advantages over other storage technologies from the technical point of view such as:

- is more compact for the same electric capacity,
- has more stable operation over time (does not loose efficiency over years),
- has functionality of both thermal and electric storage,
- does not depend on geographical features,
- can be used as seasonal storage.

Three realistic business models have been developed and analyzed for CHEST system:

1. CHEST as a provider of aggregated services in a minigrid;
2. CHEST vs. pumped hydro;
3. CHEST as an alternative to DSO investment for grid reinforcement.

In Denmark, with increasing heat and electricity prices, using the CHEST system in the context of an industrial park seems to give a good business case, where waste heat and electricity are being produced, exchanged, and therefore reused by several industries. The studied configurations are profitable, as long as the operating hours of the systems are maximized (both heat pump and ORC can run simultaneously during some hours), the heat is provided for free (and includes a minor participation from the industries providing the waste heat), and the CAPEX of the CHEST system is minimized (the future price is used in the study and accounts for cost reduction for both storage and integrated HP-ORC system). Another way to minimize the CHEST system CAPEX, the size of the system should be as large as possible, in order to benefit from the economies of scale. A good starting point would be a heat input of 500 kW at the evaporator of the heat pump. If a high temperature source and hence the higher price of waste heat is available on site (see sensitivity analysis when using a low-price district heating, Figure 18) then the CHEST system alternative would be much less economically interesting. It should also be noted that the favourable tax system in Denmark, which encourages the use of electricity to produce heat, is very favourable to the Danish business case. Without such a measure, the business case would be less interesting for all parts involved (as shown by the results from Table 22). Another way to make the CHEST business model profitable could be to put a power purchase agreement in place. These kinds of measures depend on the country where the technology will be implemented and highlight the importance of appropriate regulations to ensure the feasibility of CHEST as a way to store renewable energies.

CHEST could be an option for electricity storage in the areas without cliffs and water reservoirs thanks to the fact that its operation is independent from the geographical location. Neglecting the low-temperature subsystem, CHEST prototype can act as a full Power-to-Power storage system, hence operating like a PHS. The typical operation on an annual basis of a PHS was compared with the Power-to-Power operation of CHEST under different techno-economic scenarios and adopting different operating logics. The results of the economic analysis were compared with a business model that was defined taking the cue from a real PHS operating in the North-West of Italy. Although the IRR is higher in case of PHS, the net profit of CHEST system exceeds the value of PHS in some logics. None of the studied solutions (neither PHS) reaches the investment breakeven during the considered lifetime (30 years) since all the IRR values resulted to be negative. CAPEX for CHEST now is high but it has potential to be profitable: in the future market scenario, if CAPEX is reduced from current estimations, the IRR of the CHEST system almost equals the IRR of the pumped hydro plant. Therefore, it is concluded that the implementation of the CHEST system might be not profitable at present under the assumed boundary conditions and logics, given the high investment costs in the current market scenario and the relatively low net profit generated by its operation on the electricity market. However, it was found that CHEST can give in the future scenario similar IRR values to PHS. Hence, a disrupting and rapid technological development (bearing in mind that CHEST is currently at a low TRL) and an increase of the market for PHS and CHEST system components is necessary to reduce the gap with other solutions (this might be read also considering the electric energy storage solutions as a whole, as the economic framework should be further improved via incentives, lower taxes etc. to enable these technologies to rapidly access the market and be competitive). Moreover, participation of CHEST system to the market of ancillary services would provide an extra-profit that might ensure a higher internal rate of return of the investment.

The widespread and unavoidable diffusion of renewable energy sources will soon imply the need of massive intervention to retrofit and revamp the existing transmission and distribution grids. As an alternative to the massive reinforcement of the grid sections that are not able to dispatch and manage properly such amounts of energy, solutions for the storage, conversion and time-shift of renewable energy are available as well. Acting as Power-to-Power system, CHEST system may accomplish this task in critical grid sections: during sunlight hours, the energy overproduction of the PV plant (i.e., the share that would be otherwise curtailed) is used to run the HP. Heat stored is then used in the evaporator of the ORC at night to generate electric energy that is sold to the grid. The economic viability was compared with the option of grid reinforcement. The research question of this business case can be summarized as follows. Provided a newly installed RES plant of **y** MW connected to a distribution line with a certain dispatching limit (5-80% of the newly installed PV capacity), what is the total investment cost (capital and O&M costs) to realize

- an on-site Power-to-Power CHEST system vs.
- a new distribution line,

in order to avoid the curtailment of PV energy? Since the cost of a new distribution line strictly depends on its length, which is the **x** distance associated with the breakeven of the two solutions?

The CHEST system is expected to operate in a more frequent way during summertime, when higher energy fluxes from the PV plant cannot be fully dispatched by the grid. The magnitude of the grid bottleneck directly affects the switch-on and -off events of the CHEST system and the power rate of the HP/ORC components. In the default configuration, CHEST system was coupled with a PV plant of 50 MW and connected to a distribution line with a dispatching threshold of 40 MWh (80% of the PV size). In this case, only 3% of the PV production (about 2,71 GWh/y) would be curtailed and, to avoid it, the overproduction is used to run the heat pump. In fact, the HP is characterized by a very low capacity factor. When the grid experiences massive limitations on the amount of energy that can be dispatched without any issue, CHEST system may play a pivotal role in the correct management of energy fluxes, relieving the grid of congestion when non-schedulable renewable plants work at maximum power. The effect on technical KPIs of variations of the efficiency of system components was analyzed.

The economic results of the base case study (50 MW PV plant connected to an 80%-uncongested grid) were compared with two scenarios for grid reinforcement. The high costs of CHEST components represent an important penalty for the CAPEX of the system. 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. However, considering the variable electricity day-ahead price profile of 2019 in Italy, the IRR of the investment for a new 50-MW PV plant equipped with a PtP CHEST system would be negative. The breakeven grid length should be about 190-450 km: there is no room for the CHEST system to compete with the alternative of grid reinforcement in the reference case study and with electricity prices of 2019.

To identify how this business case for the CHEST system in future market scenarios would impact the internal rate of return of the investment and the breakeven grid length different electricity prices (fixed through the while year electricity price in range between 50-500 €/MWh are used instead of 2019 data) and the grid dispatching threshold were used for the assessment. The CHEST system starts to be more interesting if coupled with PV plants characterized by small sizes (≤ 10 MW). In case of distribution lines that are not affected by heavy dispatching limitations (40-80% of threshold value), the breakeven length reduces to less than 100 km. Notice that positive IRR values are reached in future market scenario, when the PV plant is connected to a grid with heavy limitations and in market scenarios with higher day-ahead market price: in this case, the installation costs are more than counterbalanced by the profit from energy sale and energy curtailments (especially during summertime) are avoided.

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