ATLANTIS PRESS

Atlantis Highlights in Engineering, volume 4

13th International Renewable Energy Storage Conference (IRES 2019)

Energy system design for deep decarbonization of a sunbelt city by using a hybrid storage approach

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***Abstract*—With continuously falling cost of renewable power generation and ambitious decarbonization targets, renewable sources are about to rival fossil fuels for energy supply. For a high share of fluctuating renewable generation, large-scale energy storage is likely to be required. In addition to selling electricity, the reliable supply of heat and cold is a further interesting revenue pool, which makes hybrid storage technologies an interesting option. The main feature of hybrid energy storage – as defined here - is to offer charging and especially discharging in different forms of energy by combining different charging, discharging and storage devices. They can address various demands (e.g. electricity and cold) simultaneously. Two hybrid storages, pumped thermal energy storage (PTES) and power-to-heat-to-x (x: heat and/or electricity) energy storage (PHXES), are investigated based on a techno-economic analysis within this work. Both hybrid storage technologies are charged with electricity and can supply heat and electricity during discharging. They are implemented into a simplified energy system model of a prototype city in the earth's sunbelt in the year 2030 to find a cost-optimal configuration. Different cases are evaluated: a power-to-power case (P2P), where only an electric demand must be addressed and a power-to-power-and-cooling (P2P&C) case, where the electric demand from the P2P case is divided into a residual electric demand and a cooling demand. For both cases, a natural gas-based benchmark scenario and a decarbonized, renewable-based scenario including the hybrid energy storage technologies are calculated. Both, total expenditures and CO_2 emissions are lower in the P2P&C scenarios compared to P2P scenarios. PHXES plays a major role in both cases. PTES is part of the cost-optimal solution in the P2P&C decarb scenario, only if its specific cost are further decreased.**

***Keywords*—Hybrid energy storage, Energy system modeling, Decarbonization**

I. INTRODUCTION

Worldwide, technological development and cost reduction lead to a constantly increasing share of renewable power generation (e.g. solar photovoltaics, PV) [1]. Furthermore, renewable capacity addition is preferred over fossil-based generation technologies due to some regulatory framework conditions, as well as political and social goals. Energy generation from PV and wind is strongly dependent on the weather and therefore highly fluctuating. Flexibility measures on different scales are likely to be required. Therefore, energy storage technologies, e.g. batteries, pumped hydro energy storage or thermal energy storage, gain more and more interest. They all have the common characteristic that they offer charging and discharging in the same form of energy. Within this work, they are called conventional energy storage technologies.

Recent studies state that especially the heat and cold sector shows a high potential of carbon dioxide (CO_2) emission reduction [2]. CO_2 emissions in this sector were about 14 % higher than from electricity generation in the EU in the year 2010.

In order to use the CO_2-neutral renewable electricity in the heat and cold sector, hybrid energy storage technologies can be used. Following a sector coupling approach, they offer charging and discharging in different forms of energy (electricity and/or heat and/or cold) by combing different charging, discharging and storage devices.

Rapidly changing boundary conditions in energy systems worldwide create unclear requirements towards energy storage technologies. Different technology options exist and offer different economical or environmental storage parameters: sometimes, a cost-optimized storage could be better than an efficiency-optimized one and vice versa [3]. In order to analyze the value of hybrid against conventional storage technologies, this work includes the energy system modeling for a prototype city in the earth's sunbelt. The influence of decarbonization and the integration of a district cooling system will be evaluated.

II. Hybrid energy storage

Two different hybrid energy storage concepts are investigated within this work: pumped thermal energy storage (PTES) on the one hand, and power-to-heat-to x energy storage (PHXES) on the other hand. As described in literature, both concepts are only applied as power-to-power storages [4, 5]. As both include thermal storages, they can be used in a hybrid way by taking hot and/or cold thermal energy from their storages in order address thermal demands in terms of a sector coupling approach.

A. *Pumped thermal energy storage (PTES)*

During charging, electricity is utilized by a heat pump cycle to generate a temperature difference between a hot (above ambient) and a cold (below ambient) reservoir in the form of two thermal storages. During discharging, the temperature difference is used to power a heat engine cycle thus generating electricity. Alternatively, heat and cold from the thermal storages can directly be used to address thermal demands, as shown in Fig. 1.

The combination of a heat pump and a heat engine allows for theoretically 100 % roundtrip efficiency:

$$\eta_{\mathrm{RT}}^{\max} = \mathrm{COP}_{\max} \cdot \eta_{\mathrm{Carnot}} = \frac{\bar{T}_{\mathrm{hot}}}{\bar{T}_{\mathrm{hot}} - \bar{T}_{\mathrm{cold}}} \cdot \frac{\bar{T}_{\mathrm{hot}} - \bar{T}_{\mathrm{cold}}}{\bar{T}_{\mathrm{hot}}} = 1 \quad (1)$$

Various configurations have been proposed in literature:

- PTES based on a Brayton cycle with packed beds [6–9], sensible molten salt [5] or concrete as thermal storages [10, 11].
- PTES based on transcritical CO_2 with water as hot storage and latent water/ice as cold storage [12–14].
- PTES based on conventional steam (Rankine) cycles with concrete and latent molten salt as hot storages. Ambient air is used as cold reservoir [15].

Within this publication, PTES will be based on a Brayton cycle with argon as working fluid and packed beds as hot and cold thermal storages.

For PTES, future development is expected in terms of

- turbomachine integration and reverse operation: same equipment for charging and discharging [4, 6],
- thermal storage development: avoidance of pressurized packed beds [5].

B. *Power-to-heat-to-x energy storage (PHXES)*

During charging, a resistive heater is used to generate heat using electricity. The heat is then stored in a thermal storage. During discharging, heat coming from the storage is fed into a heat recovery steam generator driving a steam power plant. Alternatively, heat from the thermal storage can directly be used to address a heat demand. Packed beds [16, 17] and sensible molten salt [4] have been proposed as storage material. A scheme of a hybrid PHXES can be found in Fig. 2.

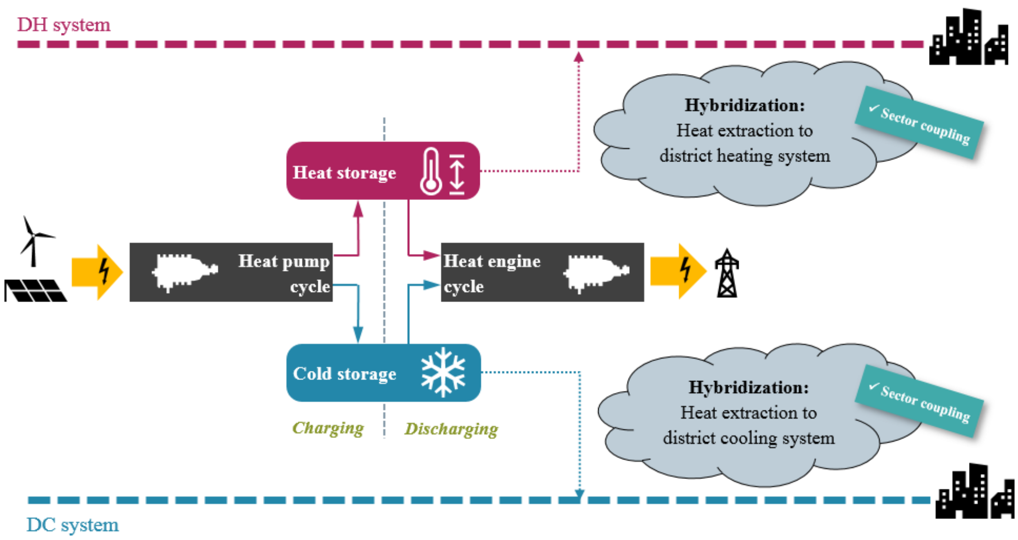

Fig. 1 Scheme of a hybrid PTES

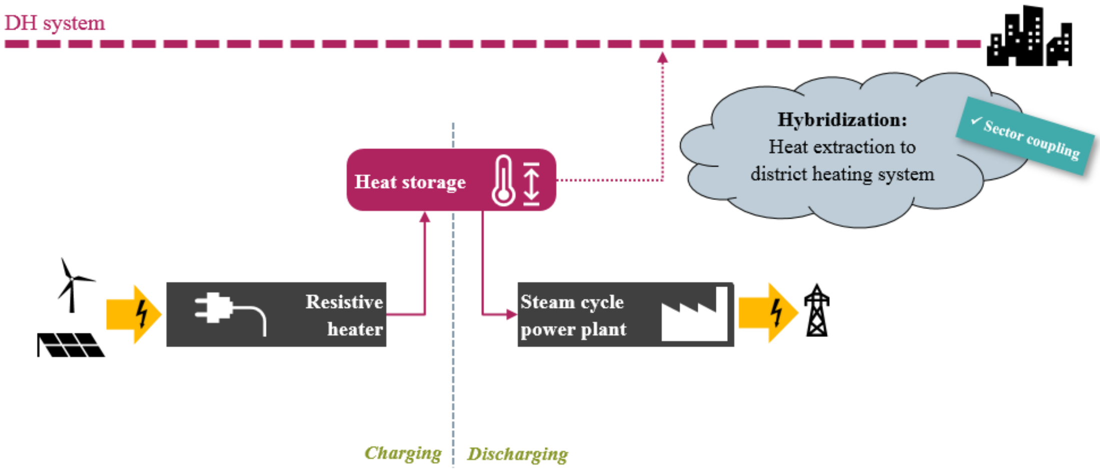

Fig. 2 Scheme of a hybrid PHXES

The Carnot efficiency is the upper limit for the roundtrip efficiency:

$$\eta_{\mathrm{RT}}^{\max} = \eta_{\mathrm{Carnot}} = \frac{\bar{T}_{\mathrm{hot}} - \bar{T}_{\mathrm{cold}}}{\bar{T}_{\mathrm{hot}}} = 1 - \frac{\bar{T}_{\mathrm{cold}}}{\bar{T}_{\mathrm{hot}}} \qquad (2)$$

Within this publication, PHXES will be based on sensible molten salt as thermal storage.

For PHXES, future development is expected in terms of cheaper thermal storage concepts and materials.

C. Techno-economic analysis

As literature data is based on various boundary conditions, the corresponding data in terms of roundtrip efficiency and specific cost is not comparable. Therefore, a techno-economic analysis is done for PTES and PHXES to have a comparable data base. Thermodynamic flowsheet simulations using the software ChemCAD ([18]) based on comparable boundary conditions (e.g. realistic turbomachine efficiencies and pinch temperatures) are combined with an equipment based cost estimation [19]. Equipment cost are then converted to installed cost using an installation factor for assembling the equipment, piping, instrumentation etc.

Based on this, a roundtrip efficiency (power-to-power) of ~58 % for PTES and ~42 % for PHXES is calculated.

The cost function for thermal storages in [19] has been updated and is now based on a pressure vessel calculation. The cost of each thermal storage is calculated based on the corresponding process conditions (upper temperature, lower temperature, pressure) coming from the flowsheet.

Power specific cost can be calculated to be 2770 €/kW$_{\mathrm{el,out}}$ for PTES and 1070 €/kW$_{\mathrm{el,out}}$ for PHXES. Storage specific cost are 23 €/kWh$_{\mathrm{th}}$ for PTES (combined value for hot and cold storage) and 13 €/kWh$_{\mathrm{th}}$ for PHXES.

Since future developments might result in cost reductions, a sensitivity analysis is applied to show the influence of a 50 % cost decrease of PTES converters and thermal storages and PHXES thermal storages.

III. Energy System Modeling

An energy system model is created for the prototypical city. The model finds cost-optimal

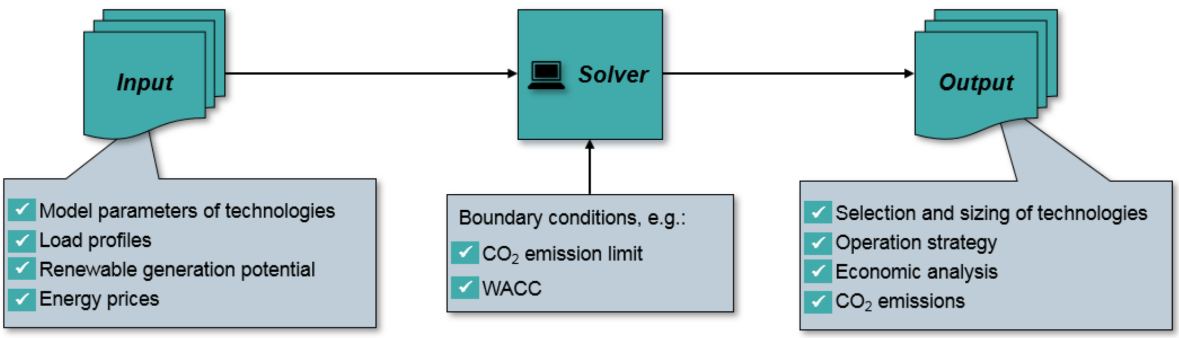

Fig. 3 Overview of energy system model inputs and outputs

Table 1 Overview of scenarios and assumptions for the year 2030

Scenario	Assumptions	Emissions	Demands [20–22]	Peak [20–22]
P2P Base	➢ Only electricity (cold demand included in electric load)	No limit	20.6 TWh_{el}	3.3 GW_{el}
P2P&C Base	➢ Sector coupling with explicit modeling of cold demand	No limit	10.6 TWh_{el} 30.2 TWh_{th}	2.0 GW_{el} 5.3 GW_{th}
P2P Decarb	➢ Only electricity (cold demand included in electric load) ➢ Hybrid storage available	-80 % of P2P&C Decarb	20.6 TWh_{el}	3.3 GW_{el}
P2P&C Decarb	➢ Sector coupling with explicit modeling of cold demand ➢ Hybrid storage available	-80 % of P2P&C Decarb	10.6 TWh_{el} 30.2 TWh_{th}	2.0 GW_{el} 5.3 GW_{th}

solutions for the investment in generation, storage, and transmission technology while considering the hour-by-hour matching of demand and supply. The matching includes different types of energy forms, in this case electricity and cold demands.

The model is classified as multi-modal energy model and could also include further sectors like transport and chemicals/fuels, amongst others. An overview of the model and its major inputs and outputs is given in Fig. 3

IV. Energy system model for a prototype city in the earth's sunbelt

The scope of the study will be a city located in the earth's sunbelt in the year 2030 with structures that are deduced from Dubai but should be interpreted as a representative instance. For the prototypical city, we assume one million inhabitants and scale the data from Dubai accordingly (Table 1). Also, the characteristic generation from PV is computed for a location close to Dubai.

A. *Structure of scenarios*

Two major cases are distinguished: one where the cooling demand is indirectly included in the electric load (called P2P; power-to-power) and one where a sector coupling approach is considered (called P2P&C; power-to-power-and-cooling). In the latter, the demand for cold is modeled explicitly and additional cooling technologies are implemented. For both cases, a decarbonization scenario is computed, reducing the maximally allowed emissions to 80 % of the P2P&C base scenario. An overview of the scenario assumptions is given in Table 1.

B. *Input data*

The model requires information on the demands and the available technologies for generation and storage.

1) *Technology data*

The model includes different electricity generation devices in terms of a combined cycle power plant (CCPP) and PV, storages in terms of heat (HWS; hot water storage), cold (IS; ice storage) and batteries (BAT) as well as cold generation devices in terms of compression chillers (CC) and absorption chillers (AC). For each technology, several techno-economic data sets are required, e.g. investment and operation costs or efficiencies. Table 2 gives an overview of the most important input data influencing optimization results.

Table 2 Overview of technology assumptions for the year 2030

Electricity generation	***Invest (€/kW)***	***Efficiency (%)***	***OM (% invest)***	***Storage (€/kWh)***
CCPP [23]	500	60_{el} / 30_{th}	3.5	-
PV [24]	352	-	1.5	-
Storage				
Battery (Li-ion) [22, 25]	275	86	5	94
Cold (ice) [26]	-	100	-	20
Heat (water) [27]	-	100	-	5
PTES	2770	$58_{el\text{->}el}$	3.5	23
PHXES	1070	$42_{el\text{->}el}$	3.5	13
Electrolyzer [24]	500	67_{LHV}	2	9
Cooling				
Compression [28]	294	Temperature dependent	3.5	-
Absorption [28]	200	Temperature dependent	5	-

Lifetime of all technologies is expected to be 20 years. WACC of 5 % is used for PV and of 8 % for all other technologies [29]. The CCPP can be operated using hydrogen from an electrolyzer or natural gas. A gas price of 25.4 €/MWh_{LHV} is assumed [30] with CO_2 lifecycle emissions of 0.25 kg_{CO2eq}/kWh [31]. Electrical transmission is considered to connect the large-scale PV generation outside of the city. Specific cost of 2000 €/kW/a are assumed.

2) *Time series data for demand and PV generation*

Both the demand profiles (electricity and cold) as well as the generation from PV follow characteristic patterns. The profile for PV is derived from Dubai weather data [32] and the overall electric load profile for the P2P case is synthesized using real hourly, daily and seasonal data [20, 21, 33]. An illustration of the data is given in Fig. 4.

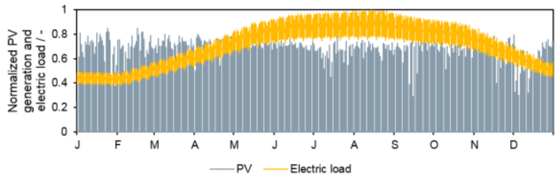

Fig. 4 Normalized PV generation (P2P and P2P&C) and overall electric load profile (P2P)

In addition, the cold demand profile is illustrated in Fig. 5, showing a strong seasonality with significant higher cooling demand in summer times. It is computed using a corrected sigmoid function with a correlation to the hourly temperature. The overall electric demand profile (used in the P2P case and shown in Fig. 4) is reduced by this cooling need (assuming a standard compression chiller) in the P2P&C case. The residual electric load profile in the P2P&C can also be found in Fig. 5.

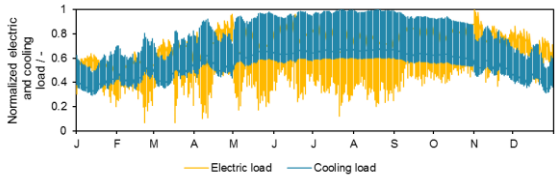

Fig. 5 Normalized residual electric and cooling load profile (P2P&C case)

All this data is put together in the model and cost-optimized systems are computed under different assumptions for technology availability and emission allowances. The next section describes major outcomes and findings of the conducted model runs.

V. Energy System Modeling Results

A. Base scenario

By just assuming an overall electric load within the P2P case, the optimal solution is relatively simple for the base scenario (Fig. 6 a). As neither renewable generation nor hybrid storages technologies are allowed in the scenario, the optimizer builds a 3.3 GW_{el} combined cycle power plant adjusted to the overall electric peak. Additionally, a small battery with a capacity of 22 MWh_{el} is included in the optimal solution. TOTEX cost are calculated to be 1.6 bn EUR and CO_2 emissions to be 8.6 Mt.

By splitting the overall electric load into a residual electric load and a cooling load in the P2P&C case, the cost-optimal solution contains more components (Fig. 6 b). A 2.6 GW_{el} CCPP is used to address the electric load and to operate a 3.5 GW_{el} compression chiller. Cold coming from the compression chiller can be temporally decoupled from generation schedule of the CCPP by an ice storage with a capacity of 5.5 GWh_{th}. Heat coming from the CCPP can be stored in a 3.0 GWh_{th} hot water storage and is then fed to a 0.9 GW_{th} absorption chiller. No ice storage is built for the absorption chiller, as its cold generation can be temporally decoupled from the heat generation of the CCPP using the hot water storage, which is cheaper than an ice storage. TOTEX cost are calculated to be 1.4 bn EUR and CO_2 emissions to be 7.6 Mt. This means that CO_2 emissions can be decreased by about 12 % by looking at electricity and cooling.

B. Decarbonization scenario

In the decarb scenario, the CO_2 emissions are restricted to 1.52 Mt CO_2 for the P2P and the P2P&C case. This value is a reduction of CO_2 emissions by 80 % based on the P2P&C base scenario.

In the P2P case (Fig. 7 a), solar PV with a capacity of 14.0 $GW_{el,peak}$ is built. The CCPP capacity is drastically reduced to 1.4 GW_{el} to meet the CO_2 emission boundary condition of 1.52 Mt. A large-scale battery with a capacity of 18.2 GWh_{el} and a large-scale PHXES with a capacity of 22.2 GWh_{th} are part of the

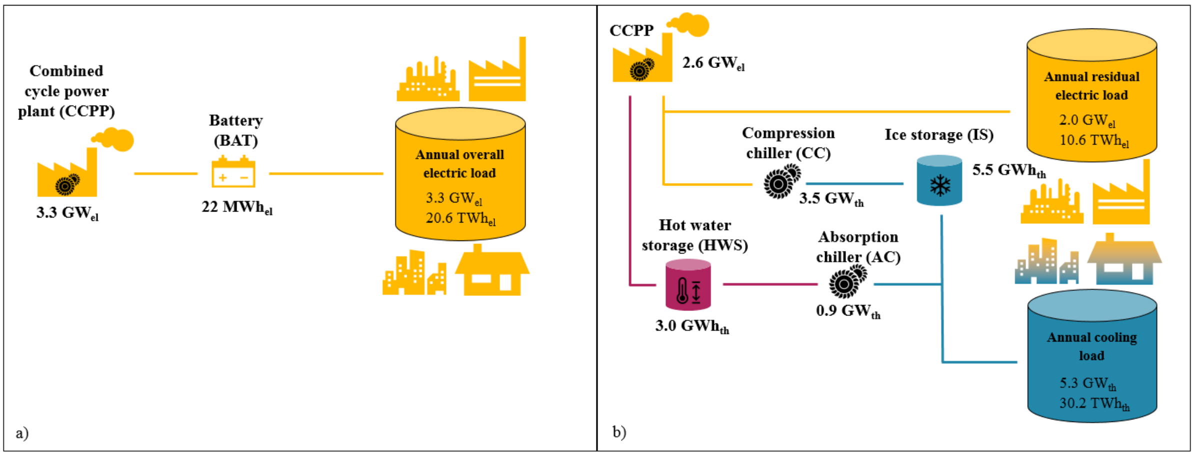

Fig. 6 Cost-optimal solution for the base scenario in the P2P case (a) and in the P2P&C case (b)

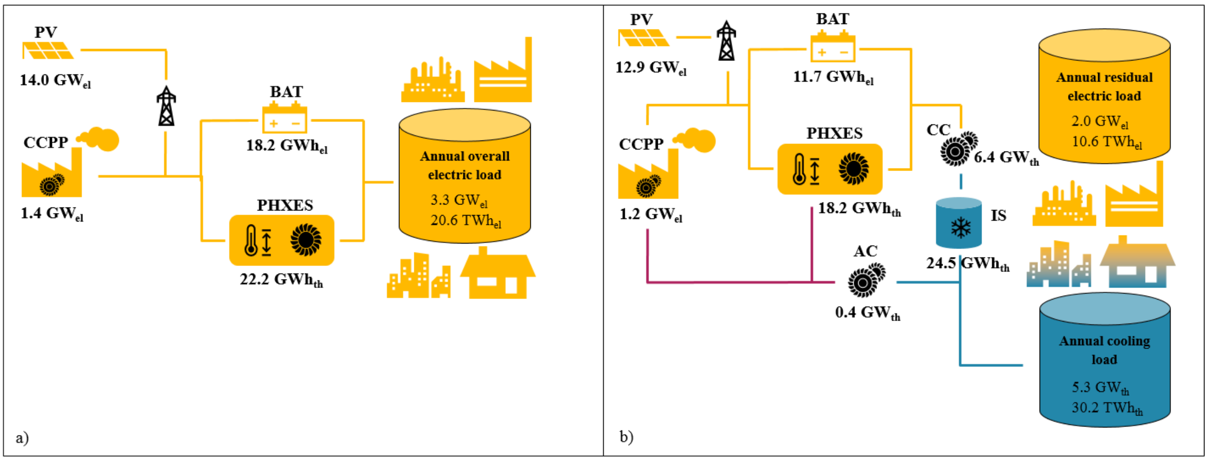

Fig. 7 Cost-optimal solution for the decarb scenario in the P2P case (a) and in the P2P&C case (b)

cost-optimal solution. TOTEX cost are about 1.8 bn EUR, which is about 12 % more than in the corresponding base case.

Solar PV also plays a central role in the P2P&C scenario to meet the CO_2 emission restriction of 1.52 Mt (Fig. 7 b). With a capacity of 12.9 GW$_{el,peak}$, it generates most of the needed electricity. It is supported by only 1.2 GW$_{el}$ CCPP capacity. Electricity can be stored in a 11.7 GWh$_{el}$ battery and an 18.2 GWh$_{th}$ PHXES. The optimal solution includes a 6.4 GWh$_{th}$ compression chiller combined with a 24.5 GWh$_{th}$ ice storage. Heat generated by the CCPP and about 15 % of heat from the PHXES thermal storage is used to operate a 0.4 GWh$_{th}$ absorption chiller. In this scenario, no hot water storage is needed compared to the base scenario, as its function is replaced by the PHXES. TOTEX cost for a decarbonization of 80 % are about 1.6 bn EUR, which is about 16 % more than in the corresponding base case.

It can be seen that the cost-optimal decarbonization of both model energy system results in large-scale renewable power generation and significant storage capacities. PHXES plays a major role in both decarb scenarios. Inter alia, the hybrid use of PHXES leads to about 11 % smaller TOTEX cost in the P2P&C decarb scenario compared to the corresponding P2P scenario.

A comparison of TOTEX cost and CO_2 emissions for both cases including all scenarios can be found in Fig. 8.

C. Cost reductions of hybrid energy storages

PTES is not part in any of the cost-optimal solutions shown above. As already mentioned, specific cost for PTES converters and thermal storages might be decreased by further developing the technology. For a sensitivity analysis, a cost reduction of 50 % due to turbomachine integration and thermal storage development is assumed. In the same way, specific cost for PHXES thermal storage are decreased by 50 %, potentially due to a different thermal storage technology. Therefore, the decarb scenario is recalculated for the P2P and the P2P&C case based on the reduced cost data. Installed thermal storage capacities of the hybrid storages can be found in Fig. 9.

Reducing the specific cost of PTES does not lead to PTES being part of the cost-optimal solution in the P2P case. Therefore, nothing changes and only PHXES

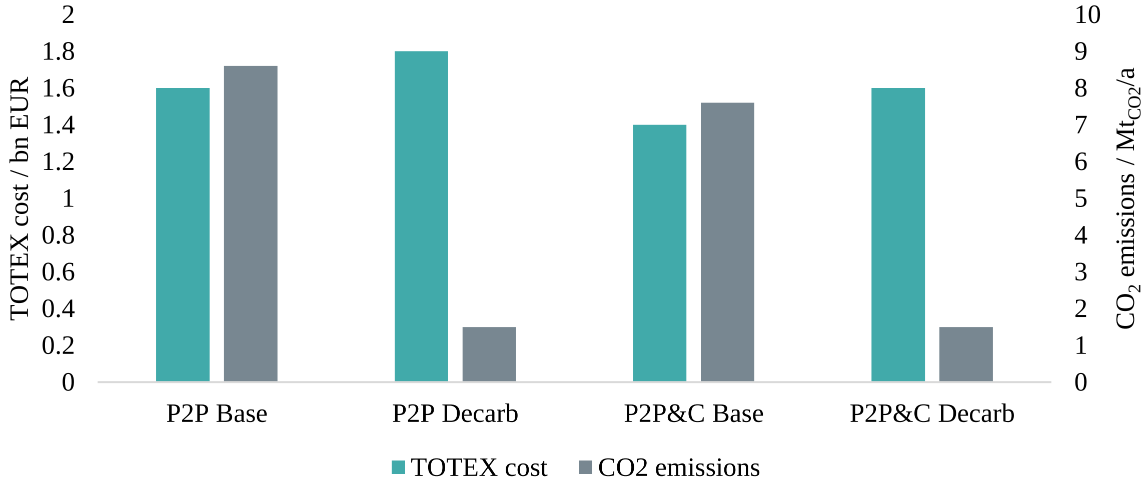

Fig. 8 Comparison of TOTEX cost and CO_2 emissions in both cases

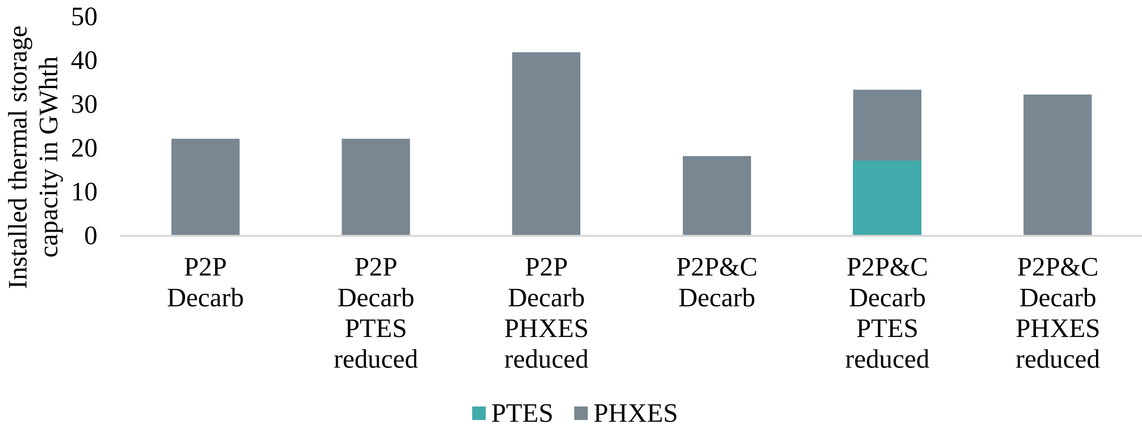

Fig. 9 Comparison of installed thermal capacities of hybrid energy storages in cost reduced decarb scenarios

with a thermal storage capacity of 22.2 GWh_{th} is part of the cost-optimal solution. When PHXES specific cost are reduced, the thermal storage capacity of PHXES almost gets doubled in the P2P case.

Within the P2P&C case, things change. Reducing the specific cost of PTES leads to its large-scale installation with a thermal capacity of 17.2 GWh_{th}. The generated and stored heat and cold within PTES are used to drive the absorption chiller, to directly address the cold demand and for the conversion back to electricity.

Although PHXES cost are not reduced within this calculation, it also plays a major role with a thermal capacity of 16.2 GWh_{th}. Reducing the PHXES specific cost leads to an increase in thermal capacity from 18.2 GWh_{th} to 32.3 GWh_{th}.

VI. Conclusion and Outlook

It is widely accepted that high shares of renewable generation in future decarbonized energy systems create a strong need for energy storage technologies. Nonetheless, the relative importance of different storage technologies is a controversial topic and therefore widely discussed. By simultaneously providing electric and thermal energy, hybrid energy storage seems to be a promising solution. Two variants of hybrid energy storage, PTES and PHXES, are investigated using a techno-economic analysis. Using the results as input for an energy system analysis of a prototype city in the earth's sunbelt, the role of PTES and PHXES compared to state-of-the-art energy converters and storage technologies is evaluated. A power-to-power case (P2P; thermal energy needed for cooling is indirectly included in the electric demand profile) is compared to a power-to-power-and-cooling case (P2P&C; electric and cooling demand are investigated separately).

The results of the energy system modeling show that cost-effective decarbonization requires a holistic energy transition ("Energiewende") instead of only a power transition ("Stromwende"). By individually looking at electricity and cooling in the P2P&C case, TOTEX cost as well as CO_2 emissions can be reduced.

It can also be seen that no single technology is the key. All cost-optimal solutions are based on combinations of different technologies with different purposes. Therefore, a systemic approach as shown in this work is important.

Hybrid energy storage can play a major role in future decarbonized energy systems. Large-scale PHXES is part in all of the cost-optimal solutions (P2P and P2P&C). PTES is part of the cost-optimal solution in the P2P&C decarb scenario, if specific cost can be reduced by about 50 % for converters and thermal storages. If heat and/or cold of PTES cannot be used in a hybrid way (as in the P2P case), it is not part of the cost-optimal solution.

Due to rapidly changing boundary conditions in energy systems worldwide, it is not clear for which storage parameters to aim for when designing hybrid energy storages. Therefore, it is important to close the loop, i.e. to link the results of the energy system analysis with the development of hybrid energy storage technologies. The hybrid energy storages are then designed according to the specific market needs.

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