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The future role of Carnot batteries in Central Europe: Combining energy system and market perspective

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ABSTRACT

Power generation from variable renewable energies is expected to dominate the future energy supply in many countries, which will lead to an increased demand for flexibility options. Carnot batteries offer the technical prerequisites for meeting this flexibility demand and are relatively easy to scale. This paper investigates the future economic potential for Carnot batteries by coupling the energy systems optimization model REMix and the agent-based electricity market model AMIRIS. While REMix evaluates the least-cost infrastructure configuration of the energy system and the role of Carnot batteries in it, AMIRIS focuses on the corresponding profitability of these storage systems. The modelling chain is applied in a case study of a zero-emission energy system in Central Europe for the year 2050. To provide guidance for a promising technology development, a parameter scan for costs and efficiencies of Carnot batteries is performed for this system. We find that from an energy system design perspective the availability of a low-cost storage medium is a key driver for the usage of Carnot batteries. In addition, the combination of Carnot batteries with wind energy provides benefits due to the possibility of longer storage durations compared to electrochemical battery systems. Carnot battery operators can potentially realize positive annual gross profits, based on factors such as the system's design, their designated role within the energy system, and notably, their market power and bidding strategy. We conclude that the development potential of Carnot batteries must be leveraged to make them competitive with other storage technologies on a broader scale.

1. Introduction

Energy storage plays a critical role in modern energy systems [2], especially in those with high shares of wind and solar power [3]. Due to the intermittent nature of variable renewable energy (VRE) sources, balancing power demand and supply requires either spatial, sectoral, or temporal flexibility. Spatial balancing can be achieved through power grids, sectoral balancing e. g. through electric heat production and cogeneration, while temporal balancing can be achieved through the use of energy storage options. There are various types of storage options available, each with its advantages and use cases [4–6]. Pumped storage potentials across Europe are limited by topography and do not offer significant options for further expansion, except for Scandinavia [7]. Likewise, cavern adiabatic compressed air energy storage requires saline rock formations in order to benefit from a low-cost storage volume [8]. Lithium-ion batteries, in contrast, are easily scalable and widely used in the transportation sector [9], but they have risks associated with increasing costs and availability due to limited annual mining of lithium [10]. Sodium-ion batteries may offer an alternative to remove the dependency on lithium, but are not yet an established technology. Another promising option are vanadium redox-flow batteries, however the current state-of-the-art systems require additional scale-up effects for both the stack and the vanadium electrolyte in order to become an economically viable alternative [11].

The choice of storage method is further influenced by the intended storage duration. To illustrate, short-term storage can be effectively achieved through battery storage, while mid-term storage can be facilitated by pumped hydro storage. For extended durations, power-to-gas and hydrogen storage are favourable solutions [12]. For such stationary applications, energy density plays a minor role and more emphasis can be put on choosing a low-cost storage medium. Carnot battery concepts [13] can provide large-scale electrical energy storage capacities. Due to their modular nature, a wide range of different technical configurations of Carnot batteries is possible [15], but the underlying working principles stay the same: Electricity is transformed into heat and stored in a storage medium such as molten salt [14]. The stored heat is then converted back into electricity when needed using processes such as the Brayton or Rankine cycle.

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Because of these advantages, we aim at analysing the potential role of Carnot batteries in future energy systems. In addition to technical challenges, such as increasing efficiency and scaling up storage systems, it is also essential to consider their economic perspectives. Investments in storage technologies require a detailed view of future profitability potentials in electricity systems with high VRE shares. A previous study indicated a significant role of generic storage systems in the overall power system design if storage technologies can achieve storage specific costs below 35 €/kWh and a competitive role against gas turbines in the range between 35 €/kWh and 75 €/kWh [16]. Similarly, Dumont et al. [17] identified the need for a low-cost energy storage medium when considering grid-scale systems with storage times between 4 and 8 h and outlined competition against lithium-ion batteries in the long run. Furthermore, the authors of [18] propose conversion of existing coal power plants to Carnot batteries with 5 h storage times and unit costs of 100–200 €/kWh$_e$, depending on the operation regime. Achieving this low-cost storage medium can therefore enable technology competitiveness for Carnot batteries against other storage technologies such as pumped hydro storage or lithium-ion batteries and be a main driver for the integration of electricity from renewable energy sources into the overall energy system. For a large-scale integration of Carnot batteries in a Danish 100 % renewable energy systems, it is imperative that the associated costs are reduced to levels below the range of 60.5 to 66.2 €/MWh$_e$ as suggested by [19]. Other studies focus more on technical optimization of Carnot battery storage but less on the integration in future energy systems and electricity markets [20–23].

While these papers provide some first indication on the potential of Carnot batteries in future energy systems, they do not provide the full picture. Various energy systems modelling studies have shown that flexible sector coupling, such as electric vehicles [24], demand response, and thermal energy storage [25], or transmission grid reinforcement [26] can have a substantial impact on the competitiveness of power-to-power storage technologies. However, flexible sector coupling is not considered in earlier studies of the economic potential for Carnot batteries [16,17]. Furthermore, the applications and profitability of Carnot batteries on electricity markets have not been assessed in this depth. Therefore, the present paper provides insight into the potential role of Carnot batteries in future sector-coupled energy systems as well as in corresponding electricity markets and helps to identify the most promising areas for further research and development. More specifically, our research addresses the following research questions:

1) What targets for techno-economic parameters need to be achieved for Carnot batteries in order to enter into the cost-optimal energy mix of a system with competing flexibility options?
2) What are promising technological niches for the future deployment of Carnot batteries if cost competitiveness for balancing power supply cannot be reached?
3) What are the economic potentials for Carnot batteries with regard to the business-oriented perspective of storage operators and different modes of operation?

To answer the first research question, the study analyses the cost-effectiveness of Carnot batteries compared to other energy storage options. The analysis considers the costs of installation, maintenance, and operation, as well as the efficiency and lifespan of the storage systems. The second research question focuses on identifying the most promising technological niches for the deployment of Carnot batteries. This involves evaluating the potential applications and benefits of the technology, as well as the technical requirements and challenges that need to be addressed. Finally, the third research question targets the economic perspectives for Carnot batteries investigating different modes of operation. These modes of operation refer to how the storage system is utilized in the electricity market, and the economic perspectives include factors such as investment costs, operation and maintenance costs, and revenues from energy arbitrage. An analysis of these factors can provide insights into the potential profitability of Carnot batteries and inform investment decisions for their deployment in future electricity systems.

By addressing these research questions, our study effectively bridges a significant research gap, providing a comprehensive system analytical evaluation of Carnot batteries. Notably, our study extends beyond a single-country focus, encompassing a comprehensive techno-economic investigation within the context of Central Europe. Our analysis is particularly concentrated on the interaction of Carnot batteries with other flexibility options and the anticipated revenue they can generate in the electricity market. Therefore, we combine a centrally planned energy systems optimization perspective with a business-driven electricity market simulation approach. By investigating these aspects, our research not only advances the understanding of Carnot battery performance on electricity markets but also contributes to the broader discourse on the integration of storage technologies into systems with high shares of VRE. This paper is a substantial extension of the conference paper [1] presented at the International Conference on Applied Energy (ICAE2022) in Bochum, Germany, Aug 8-11, 2022.

Our paper is structured as follows. In Section 2, we describe the general model setup, design of the parameter scan on techno-economic assumptions, and the selection process of the different scenarios considered in the study. Section 3 presents the results for both the cost-optimal energy system design aspect and the market simulation. The limitations of the study are discussed in Section 4, while the conclusions and outlook for future work are presented in Section 5.

2. Material and methods

The analysis is designed around a coupled modelling system, as seen in Fig. 1. We deploy the energy system optimization model REMix [27] to find cost-optimal designs under different techno-economic assumptions, and the electricity market model AMIRIS [28] to get a more detailed view into the effects of operational decisions made by Carnot batteries in the electricity market. The model coupling is implemented using iog2x [29] which is based on the workflow manager ioProc [30] and guarantees efficient data transfer from REMix to AMIRIS. This involves processing REMix results by converting them into the required format for the AMIRIS model, while also taking care of AMIRIS execution and model result evaluation.

2.1. Parametric study with the energy systems optimization model REMix

To establish a baseline on the overall energy system design and decisions on infrastructure, we use the REMix framework for optimizing energy system models [27]. The model considers both capacity expansion planning and economic dispatch in a high spatial and hourly resolution in order to find the least-cost optimal energy system design. The technology modelling in REMix is described in detail for the power generation and storage in [31], for the power grid in [32], for the heat sector in [25], for the gas sector in [33], and for electric vehicles in [34]. Previous studies have for example focussed on the impact of national political targets on the overall design of a 100 % renewable energy system [35,36], the role of green hydrogen and methane for a climate neutral energy system under different considerations regarding limited network expansion [37], or on different modelling approaches [38]. For the case study at hand, we build upon a previously published dataset for the power system and additional technologies for the consideration of sector-integration with the heat and gas sectors [39] which is linked to the case study presented in [33]. This model encompasses Germany spatially resolved into 10 partially aggregated federal states and 12 neighbouring countries as individual model regions, as seen in Fig. 2. For the temporal resolution 8760 time steps are used in order to adequately capture the variability of feed-in from VRE sources. A cost-optimal capacity expansion planning for power plants, gas pipelines, electrical grids, and storage technologies for the model year 2050 is conducted while considering the pre-existing capacities such as

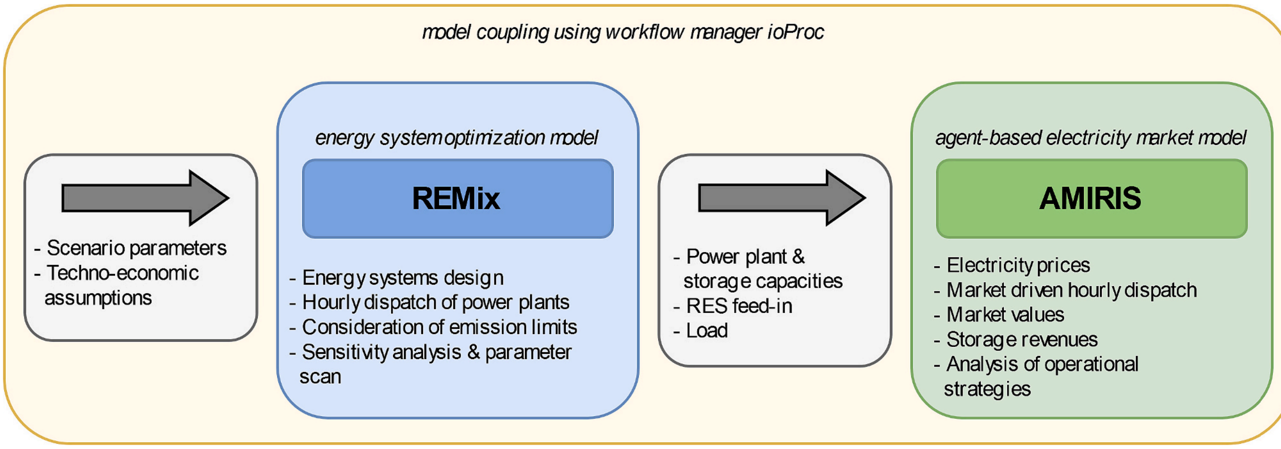

Fig. 1. Model coupling setup.

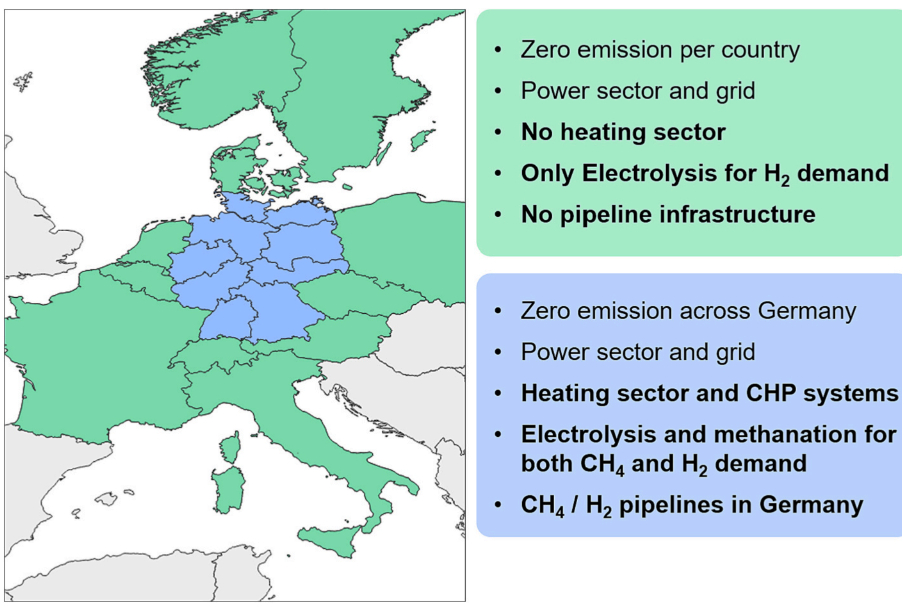

Fig. 2. Representation of the spatial scope of the case study based on [39]. While Germany is modelled as 10 aggregations of federal states and with higher sectoral detail, especially for the heating sector and the gas infrastructure for hydrogen and methane, its 12 neighbouring countries are modelled with less sectoral detail and fewer flexibility options.

pumped-hydro storage plants. In the selected case study, the main competitors for Carnot batteries are pumped hydro storage, lithium-ion battery storage technologies, and conversion to methane for subsequent reconversion to electricity. For Germany the hydrogen produced via electrolysis can be further processed via methanation units and used for electricity production in gas turbines, while in the neighbouring countries it can only be used to satisfy the exogenous demand for hydrogen. This competition is not only between different options for storing electrical energy, but also against chemical storage options in the form of hydrogen and methane, and provides a better basis of understanding on the role of Carnot batteries. In Germany, Carnot batteries are additionally competing with extended district heating networks to provide flexibility to the electricity system. By integrating thermal storage and a wide range of technologies for heat supply, including CHP plants, heat pumps, electric boilers and fuel-based boilers, district heating networks can react flexibly to the VRE supply. A detailed description of the scenario and model setup can be found in [33], the corresponding model assumptions are documented in [21].

To evaluate the efficiency and cost development required to achieve competitiveness from an energy system design perspective, we conduct a parametric variation of the techno-economic assumptions on Carnot batteries. This parametric study considers a variation of overall round-trip efficiency, capital expenditure (CAPEX) for the charging and discharging infrastructure, and CAPEX for the storage capacity. The charging and discharging capacity and energy storage volume are optimized independent from each other in order to derive the optimal design range in terms of energy-to-power (E2P) ratio.

Table 1 compares the techno-economic parameters for the Carnot batteries derived by the state-of-the-art reviews by [17,40] to those of other storage technologies considered in the case-study. Furthermore, it provides the ranges assumed in the parameter scan, which are based on the more optimistic projections on future technology development stated by [17,40]. In reality, we expect a certain correlation between the different components such as higher round-trip efficiencies leading to higher CAPEX for charging and discharging, which, for the sake of identifying ideal techno-economic configurations, is ignored in this study and all possible combinations are considered. The wide range reported in both review studies hints at the large uncertainty faced during current prototype projects and cost projections for future systems. To comprehensively reflect the uncertainty of technology

Table 1
Techno-economic assumptions for Carnot batteries and the different storage technologies in competition with each other. Values are derived from Dumont et al. [17], Vecchi et al. [40], and Gils et al. (year 2050) [39].

Storage system	Technical lifetime in years	Round-trip efficiency	CAPEX storage	CAPEX converter
Brayton Cycle, [17]	25–30[a]	60 % - 70 %	55–198 $/kWh	395–875 $/kW
Rankine Cycle (Electric heating), [17]	25–30[a]	12 % - 55 %	~94 $/kWh	~376 $/kW
Rankine Cycle (Heat pump), [17]	25–30[a]	30 % - 73 %	68–117 $/kWh	272–468 $/kW
Brayton PTES, [40]		52 % - 70 %	50–1500 $/kWh	2000–4000 $/kW
Rankine PTES, [40]		45 % - 65 %	250–1000 $/kWh	500–8000 $/kW
LAES, [40]		40 % - 60 %	400–800 $/kWh	700–3000 $/kW
Power to gas (methane), [39]	25 / 25 / 30	45 %[b]	0.2 €/kWh	350 / 800 / 850 €/kW[c]
Lithium-ion batteries, [39]	25	94 %	150 €/kWh	50 €/kW
Pumped hydro storage, [39]	60	85 %	10 €/kWh	200 / 250 €/kW[d]
Carnot battery parameter scan, [39]	25	[55 %, 65 %, 75 %]	20–150 €/kWh	90–400 €/kW

[a] Assumed lifetimes based on [41].
[b] Assumed efficiency for electrolysis 80 %, methanation 90 %, CCGT 63 %.
[c] Assumed investment costs for electrolyser, methanation plant and CCGT.
[d] Separate cost assumptions for turbines and pumps.

development, we derive a set of assumptions for each of the key input parameters. Thus, the parameter scan includes three assumptions for the round-trip efficiency (55 %, 65 %, 75 %), four for the converter CAPEX (90 €/kW, 150 €/kW, 270 €/kW, 400 €/kW), and five for the storage CAPEX (20 €/kWh, 35 €/kWh, 55 €/kWh, 70 €/kWh, 90 €/kWh).

Due to the limited potential of expansion of pumped hydro storage and methane cavern storage sites, the highest competition arises from battery systems. This also gives a rough upper limit for the allowed storage CAPEX as values above would be outcompeted in most cases due to both the higher efficiency and lower cost of the power electronics for charging and discharging. By considering all possible combinations of assumptions for efficiency and investment costs, the parameter scan includes a total of 60 REMix runs. This wide range allows the role of Carnot batteries to be assessed for scenarios where they can play a significant system-wide role, as well as for scenarios where the techno-economic data limits the deployment of the technology to a niche role.

2.2. Market analysis with the agent-based electricity market model AMIRIS

Transforming the centralized approach of cost optimal energy systems into operating energy systems, investments in technologies have to be made by individual entities. Therefore, these investments must demonstrate a favourable economic outlook in practice. In order to assess economic potentials for Carnot batteries with regard to the business-oriented perspective of storage operators, we employ the open agent-based electricity market model AMIRIS [28] to simulate the German day-ahead market. AMIRIS is implemented in the open framework for distributed agent-based modelling of energy systems FAME [42] which allows a powerful, yet flexible model parameterization [43]. AMIRIS can be utilized to explore market dynamics that arise from the interactions of market actors [44], economic assessments of battery storage [45], while also considering regulatory frameworks [46], and actors' behaviour under uncertainty [47]. AMIRIS has been calibrated and back-tested for the German day-ahead market [45] and Austrian day-ahead market [48], demonstrating a good fit in simulating historical electricity prices. All relevant configuration files and data are openly available [49]. AMIRIS represents various actors in the electricity market, including power plant operators, traders, and policy agents. We use a dedicated storage agent class who provides temporal flexibility. This agent is parameterized with techno-economic parameters such as capacity, power, charging and discharging efficiencies, availabilities, and costs. In contrast to the optimization model REMix, two distinct operational strategies for the Carnot battery agent are implemented. These strategies are described in detail in Section 2.2.1. A detailed elaboration of all other agent types can be found in [50] whereas a schematic overview of AMIRIS is found in the Appendix in Fig. 9.

2.2.1. Storage dispatch strategies

The bidding strategy of a Carnot battery as a flexibility provider is crucial for profitable operation. Various methods have been proposed in the literature to determine effective bidding strategies, including stochastic programming, game theory, and machine learning. Here, we adopt two strategies on the basis of dynamic programming that require forecasted information about the market (i.e. forecasted electricity prices) for a defined window. The algorithm evaluates the discrete states-of-charge of the Carnot battery to identify optimal charging and discharging opportunities. The resulting bids and asks are submitted to the electricity market accordingly. Specifically, we compare a system-optimal solution that minimizes system costs with a best-case, upper-limit scenario for the Carnot battery operator that maximizes profits by utilizing the market power of the total installed storage capacity and power. Both strategies optimize the operator's schedule over a 168 h window with perfect foresight.

2.2.1.1. Minimizing system costs. In order to reduce overall operational system costs associated with dispatching the power plant park, the *Minimize system costs* strategy corresponds to a flexibility provider that operates in a "system-friendly" manner. This approach minimizes the sum of the marginal costs of operating the electricity system over the forecast horizon. While minimizing system costs may not be a feasible business case for individual storage operators in reality, this approach helps to explore the potential solution space.

2.2.1.2. Maximizing profits. The *Maximize profits* strategy aims to maximize the profits of storage operators by utilizing their market power in the electricity market, especially for large-scale storage systems. Due to the assumed operator's perfect foresight and full market power, this approach represents the absolute upper limit of profits in the analyzed scenario. Typically, the storage operator seeks to charge when forecasted prices are low and discharge when forecasted prices are high. The algorithm considers the impact of the operator's own bids and asks on the merit order and its price changing effect. This effect is significant if the storage characteristics (i.e. power, capacity) are relevant to the system's total size, meaning that the storage can actually impact market prices due to its behaviour.

2.3. Scenarios and sensitivity analysis

In addition to both the parameter scan for the overall energy system design and dispatch strategies for the storage operators, several additional aspects for the energy system design can have a large influence on the role of Carnot batteries in the cost-optimal solutions. To this end we extend the "*Base*" case system of the parametric study as presented in 2.1 by three additional sub-scenarios to study the economic impacts and the sensitivity of Carnot battery expansion towards additional design objectives. The first scenario "*No Grid*" limits the available transmission lines to those planned in the ten-year network development plan from the year 2016 [51] as well as the e-Highway 2050 study [52]. This reduction in the spatial flexibility of the system is expected to lead to an increased demand for temporal flexibility options. Similarly, the second scenario "*Low Flex*" decreases the flexibility on the demand side by enforcing a capacity factor of 0.75 for the operation of water electrolysis. While technically electrolysis can be operated in a highly flexible fashion [53], this assumption emulates a hesitancy for investments into electrolysers operated solely based on surplus electricity. The third scenario "*Low Curtail*" addresses limitations in profitability for renewable energy operators by limiting the possibility for curtailment of energy from renewable sources to 5 % of their annual energy demand. This limitation of flexibility likewise increases demand for temporal storage options in the overall system design.

To further test the sensitivity of the results to the techno-economic assumptions regarding the main competing storage technologies and the composition of the VRE plant fleet for electricity generation, supplementary model calculations are carried out with REMix. Based on the parameter study, three combinations from the parameter scan in Section 3.1 are selected to test the related interactions with the techno-economic assumptions for Carnot batteries. The results of the sensitivity analysis are described and analyzed in the Appendix B.

3. Results

The analysis is presented in the order of model application. First, the REMix results on the energy systems design in the parametric study are described in Section 3.1, followed by the electricity market analysis relying on AMIRIS in Section 3.2.

3.1. *Competitiveness of Carnot batteries from an energy system design perspective*

In order to find the technical configurations in which Carnot batteries start entering the overall system design during a least-cost optimization, the full parameter scan using different techno-economic data is computed, see Section 2.1. Fig. 3 shows the share of Carnot battery capacity against the overall storage capacity from both Carnot batteries and battery storage systems. In addition, the most optimistic systems based on [17] are included as reference points. All of the configurations reported in the literature are not competitive against the assumed improvement in battery systems. However, both the Brayton cycle and Rankine cycle systems are close to being viable configurations due to their higher round-trip efficiencies. This leads to the conclusion that additional efforts in research and development or cost reductions by technological advancements are required if no support schemes are implemented. If sufficient cost reductions are achieved for either the power specific CAPEX or the storage specific CAPEX, both Brayton and Rankine systems could become cost competitive options. For lower round-trip efficiencies in the range of 55 % the target range for the introduction of Carnot batteries ranges between 400 €/kW at 20 €/kWh to 90 €/kW at 55 €/kWh. For higher round-trip efficiencies in the range of 75 % there is more leeway for higher investment costs between 400 €/kW at 35 €/kWh to 150 €/kW at 70 €/kWh. Overall, out of the 60 modelled system configurations, eight reach a share in combined storage capacity between 20 % and 50 %, ten a share between 50 % and 90 %, and nine a share higher than 90 %. However, the system configurations leading to high market shares would require significant progress along all three dimensions making a share above 50 % for Carnot batteries quite unlikely. Still, even with lower system wide shares Carnot batteries can fill a niche role specially if low energy specific investment costs are reached. As explained in the following, these niches arise especially in regions with a high wind energy share in power generation or limited flexibility in sector coupling.

A closer look into the spatial distribution of storage technologies shown in Fig. 4 reveals a close correlation between the installed capacities of wind onshore and Carnot batteries, photovoltaic capacities and battery storage systems, as well as offshore wind capacities and electrolysers. Especially for electrolysers there is a distinct concentration in the northern parts of Germany due to the availability of storage caverns for hydrogen and methane. As a consequence of the different approaches towards modelling sector integration in Germany and the remaining countries in Europe there is no significant investments in either Carnot batteries nor battery systems under most techno-economical parameter combinations in Germany. This can be explained by the high demand side flexibility provided from water electrolysis and, if necessary, methanation for electricity production in gas turbines. On the other hand, the exogenous demand for hydrogen and methane requiring at least some investments into electrolysers and therefore decreasing the marginal cost of using the technology as a

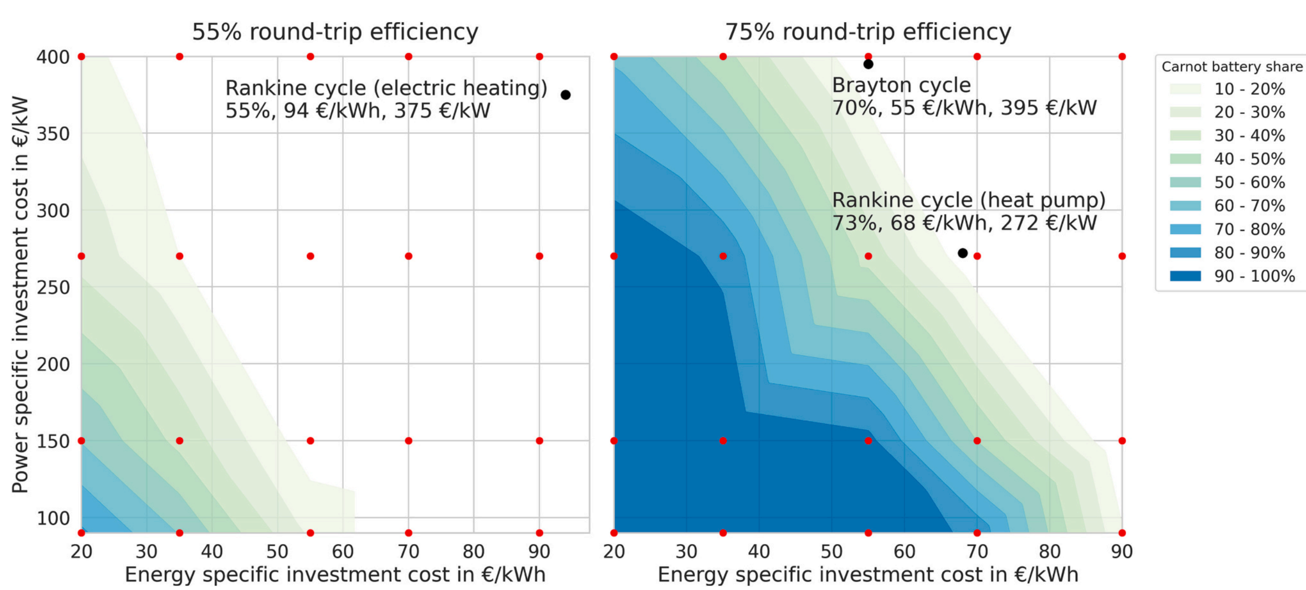

Fig. 3. Share between provided electricity from Carnot batteries and battery storage systems for the full parameter scan. Contours of the different shares are based on a linear interpolation of all points in the three-dimensional space. Red points indicate the different combinations in techno-economic assumptions, while black points indicate the most optimistic state-of-the-art system configurations identified by [17]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

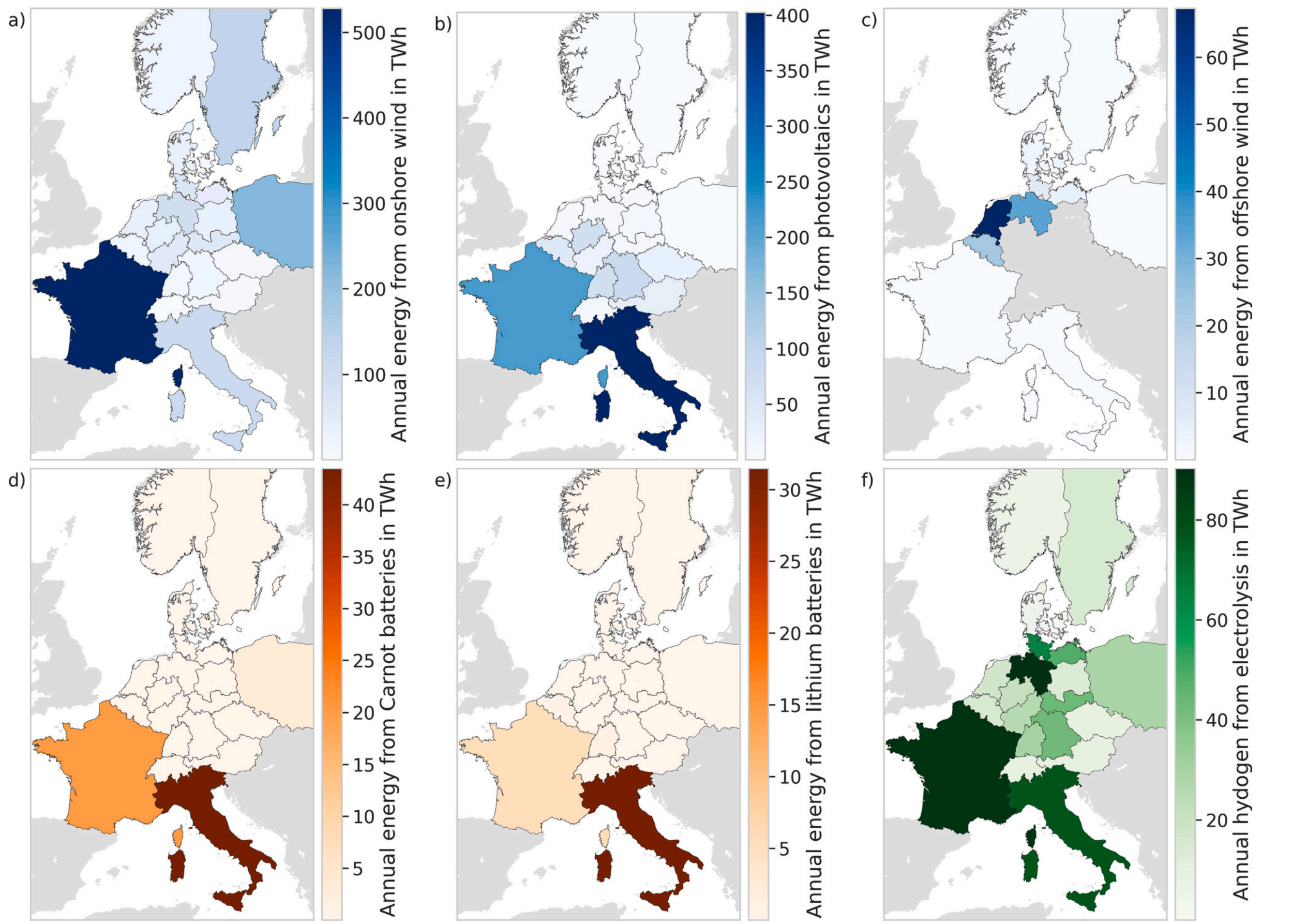

Fig. 4. Spatial distribution of annual energy generation from renewable technologies (a – c), annual energy provided from storage systems (d, e), and annual hydrogen production from water electrolysis (f). The spatial correlation indicates synergies between onshore wind and Carnot batteries as well as photovoltaics and battery storage. Values are derived from the techno-economical configuration of 65 % round-trip efficiency, 20 €/kWh storage specific CAPEX and 270 €/kW power specific CAPEX.

flexibility option. In the case of considerable optimistic technological progress for Carnot batteries (i.e. 65 % round trip efficiency, 150 €/kW, 20 €/kWh), there is some investment into Carnot batteries in Germany. This is the reason, why we focus on these cost assumptions to be further analyzed in the market assessment. The spatial distribution of Carnot batteries in Germany is presented in Appendix C.

In addition to the spatial correlation, we can consider the temporal charging and discharging pattern to further substantiate the connection between renewable technologies and storage technologies. Fig. 5 shows a clear diurnal charging pattern for battery storage systems, which matches the feed-in profile from photovoltaics and indicates most of the energy is charged during the middle of the day and discharged in the evening hours. Some additional charging and discharging at the beginning of the day allows reducing the typical electricity peak during the morning hours. In contrast, the charging of Carnot batteries has a wider band during the midday hours and is not charged every day. Storage discharging is also mainly in the evening hours, which is driven by both the exogenously provided electricity demand profile and the lack of photovoltaic generation. With respect to the storage level the clear roles of lithium-ion battery storage as a daily peak load provider and the Carnot batteries as an energy storage for multiple days can clearly be identified.

3.2. *Electricity market analysis*

In contrast to the energy systems optimization, which is performed from a central planning perspective for Central Europe, the market simulation is limited to the German market due to model constraints at time of the research design. Imports and exports to neighbouring market zones are taken as exogenous time-series from the respective REMix model runs. The Carnot battery specifications regarding power and capacity differ substantially in the investigated three scenarios (see Section 2.3), their configuration is displayed in Fig. 6. The installed power of Carnot batteries are 3.7 GW in the *Base* scenario, 15.8 GW in the *Low Flex* scenario, and up to 35.8 GW in the *No Grid* scenario. E2P ratios range from 7.4 (*No Grid*), to 8.2 (*Low Flex*). In all three scenarios, the Carnot battery's technical specifications and status as singular operator contribute to significant market influence and market power. When interpreting the following results, these characteristics are important to be kept in mind.

The profitability analysis is performed by comparing gross profits (difference between revenues from and costs for traded electricity, neglecting any other expenses) for all three scenarios and the two dispatch strategies, i. e. minimizing system costs and maximizing profits. Fig. 7 illustrates gross profits relative to the best-case scenario *Low Flex* applying the *Maximize Profits* strategy. This strategy consistently outperforms the Minimizing System Costs strategy in all regarded scenarios, attributable to the Carnot battery operator's effective utilization of its substantial market power. In all cases, positive annual gross profits can be achieved. These results represent the most upper limits of revenue potential, emphasizing the unique advantage conferred by the Carnot battery's status as the main flexibility provider. This is especially

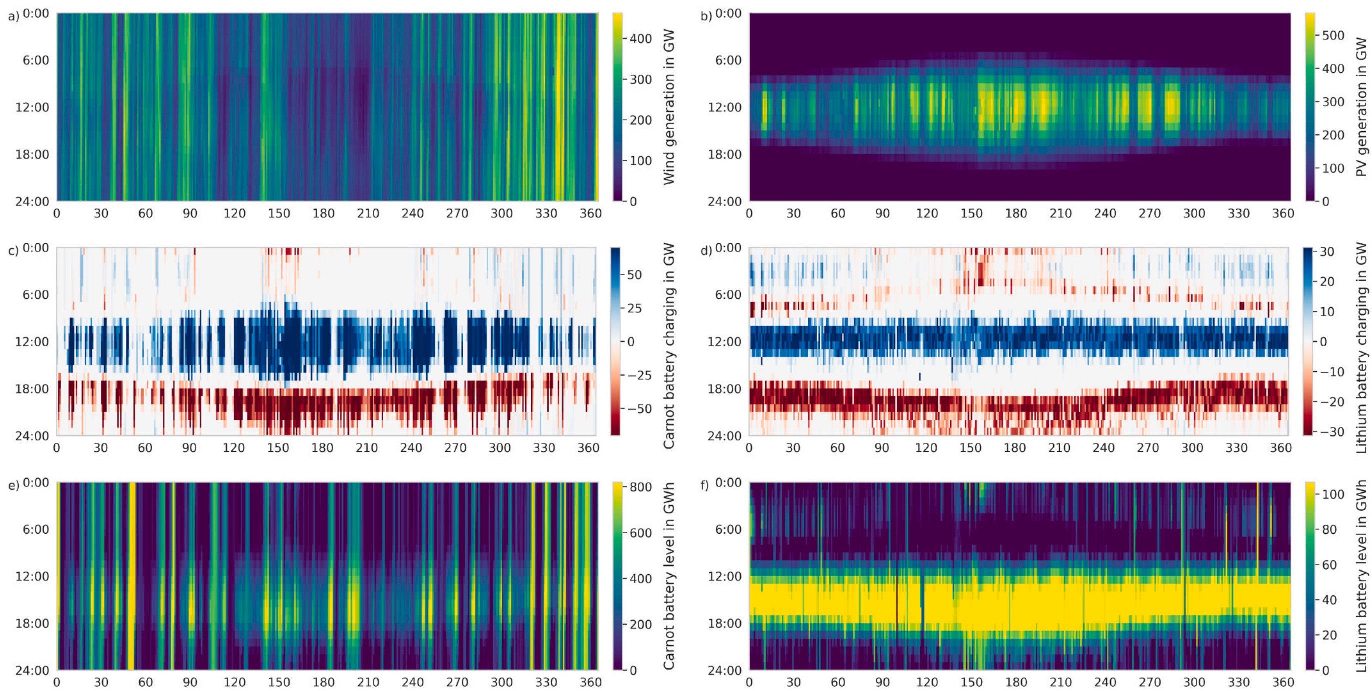

Fig. 5. Hourly feed-in from renewable technologies (top), hourly charging and discharging (middle) for batteries and Carnot batteries (middle), and storage levels (bottom) throughout the year for Carnot batteries and lithium-ion batteries. Hourly values are derived from the techno-economical configuration of 65 % round-trip efficiency, 20 €/kWh storage specific CAPEX and 270 €/kW power specific CAPEX.

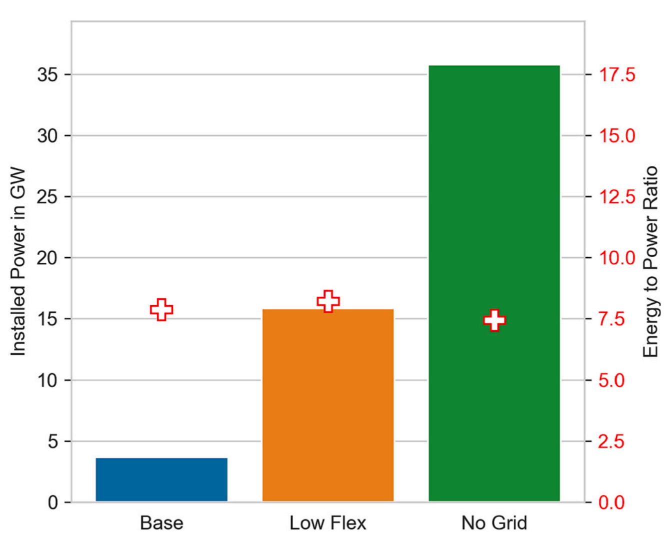

Fig. 6. Installed Carnot battery capacities and their Energy to Power ratio (red framed crosses). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

prevalent in the *Low Flex* and *No Grid* scenarios. Notably, all strategies profit from employing a rolling window of perfect foresight for arbitrage options.

Even though the Carnot battery capacity in the *No Grid* scenario is more than doubled compared to the *Low Flex* scenario, it cannot outperform the gross profits from the latter. We observe diminishing spreads in electricity prices as a consequence of arbitrage. Therefore, the increased trading capacities of the Carnot battery in the *No Grid* scenario cannot generate additional revenue potentials.

Table 2 provides additional comparative evaluation of the *Maximize Profits* and *Minimize System Costs* strategies. In this analysis, values exceeding 100 % indicate a greater impact when employing the *Maximize Profits* strategy. The *Maximize Profits* strategy also significantly influences mean prices, driving them up by at least 345 % in the *Base* scenario and as much as almost 400 % in the *Low Flex* scenario. Full cycles tend to be lower compared when aiming at maximizing profits. Total system costs (sum of all operational costs) are more than doubled (*Base* and *Low Flex*) or even tripled (*No Grid*) scenario. Regarding accumulated discharged and charged energy, the results reveal higher values in the *Base* scenario, contrasting with smaller values in the *Low Flex* and *No Grid* scenarios.

4. Discussion

The results show that with our model setup and scenarios analyzed, Carnot batteries have a limited role in the modelled optimal future energy systems for Central Europe, even with optimistic cost assumptions. This results from the extensive provision of flexibility through sector coupling technologies, such as flexible hydrogen production or advanced district heating, and from the use of battery storage, which proves to be more cost-effective for many locations. However, further development, especially based on Brayton cycles and Rankine cycles in combination with heat pumps, can make Carnot batteries a promising alternative for electricity storage. Though, the future role of Carnot batteries will likewise depend on the future development of battery storage systems and electrolysers. Both technologies can have a significant impact on the overall landscape of flexibility options. This balance may be shifted if additional factors, such as material availability or increasing prices for raw materials are considered. Therefore, additional research on the life cycle impacts of different storage technologies will be an important field of research going forward.

The REMix parameterization used here considers the power grid only in aggregate form as transmission capacities between model regions (Fig. 8). As a result, information about grid congestion within these regions is lost. Consequently, flexibility needs at the local level are partially underestimated, and so are the potentials of Carnot batteries at locations of high generation surpluses. The extent to which local wind power curtailments can be cost-effectively avoided by Carnot batteries

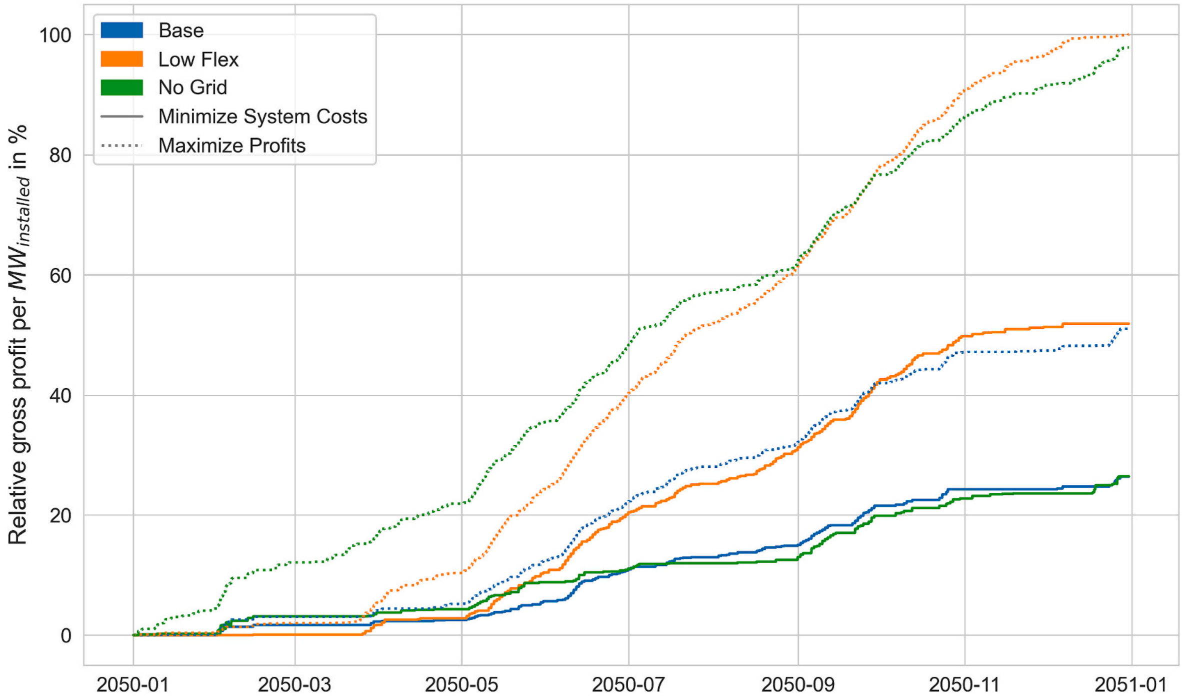

Fig. 7. Relative gross profit per $MW_{installed}$ compared to best performing combination (*Low Flex* with *Maximize Profits strategy*).

Table 2
Evaluation of the performance of the *Maximize Profits* strategy in comparison to the *Minimize System Costs* strategy, where a value greater than 100 % indicates a more pronounced impact when applying the *Maximize Profits* strategy.

	Total System Cost	Mean Price	Full Cycles	Accumulated Discharged Energy	Accumulated Charged Energy
Base	235 %	345 %	85 %	85 %	84 %
No Grid	309 %	378 %	81 %	81 %	81 %
Low Flex	262 %	395 %	80 %	80 %	80 %

thus remains to be addressed in more spatially detailed analyses.

The electricity market analysis of our study focuses on the economic analysis of Carnot batteries on the German market in future scenarios. [54] previously explored the economic viability of pumped heat electric storage on historical 2016 day-ahead prices concluding that high investment costs posed challenges for profitability. [55] simulated a Carnot battery on the scale of multiple households achieving similar results. In contrast, our results indicate positive gross profits, although with optimistic learning rates regarding CAPEX. Additionally, our work expands its scope beyond residential applications and considers Carnot batteries at a larger scale, with variations in power and capacity configurations. [56] explored the optimal sizing of Carnot batteries in combination with concentrated solar power plants, focusing on historical day-ahead prices in the Spanish electricity market and identifying E2P ratios between 5 and 10 as optimal for intraday storage purposes. Our study also suggests E2P ratios between 7.4 and 8.2 resulting in similar characteristics. Furthermore, in line with [57], who emphasized the significance of E2P ratios greater than 7 and steep electricity price increases for Carnot battery applications, our findings support the importance of the scaling of the Carnot battery for achieving profitability. In [19], the authors investigate a 100 % renewable energy system proposed for a future Danish energy system in 2045. The findings reveal that Carnot batteries have the potential to facilitate 32 annual storage cycles, in combination with significantly elevated E2P ratios. Consistent with our own results, the authors underscore the importance of decreasing storage costs to thresholds below 60.5 €/MWh_{el} and 38 €/MWhel, contingent upon the specific sub-scenario considered. When interpreting the presented results on economic perspectives the following limitations have to be considered. First, the technical assumptions and cost basis of the presented Carnot batteries follow very optimistic learning rates. The assumed storage power and energy cost assumptions of 150 EUR/kW and 20 EUR/kWh, respectively, combined with a round-trip efficiency of 65 % must be kept in mind when interpreting the market analysis results. The benefit from a more integrated system such as thermal integration of Carnot batteries with industry processes or district heating systems as well as retrofitting power plants to storage systems, or competition with other flexibility options are outside the scope of this study and may shift the conclusions on the overall energy system design and the economic profitability. Second, the scope of the electricity market analysis is limited to arbitrage trading on the German day-ahead market. This not only neglects additional revenue potentials like providing system services such as frequency restoration reserve, but also possible competition from neighbouring market zones and other flexibility providers. Third, we want to emphasize that the profitability of the *Maximize profits* strategy marks the most upper limit of possible revenues since the storage trader benefits from its total market power and makes full use of it.

5. Conclusions

We present a comprehensive analysis of Carnot batteries and assess their future role in energy systems with high shares of renewable energies. A model coupling of the energy system optimization model REMix with the electricity market simulation model AMIRIS allows an investigation on both system and market perspective. From a general energy system design perspective, we can conclude that Carnot batteries may be a promising option for mid-term energy storage if technology development makes significant progress. In terms of system parameters this translates into the need for achieving a low-cost storage medium in the range of 20–35 €/kWh. Improving the round-trip efficiency seems to be a viable secondary target, however, needs to be traded-off against increases in the capital expenditures for charging and discharging, which may increase accordingly. If this is achieved, Carnot batteries would be more viable for high energy to power ratios than lithium-ion battery storage systems. The results from the REMix model further indicate synergies between Carnot batteries in conjunction with electricity generation from wind turbines but also to a certain degree with photovoltaic and lithium-ion battery systems. However, this synergy depends on the overall need for energy storage which can be impacted by high shares of electrolysis. The results also confirm that the use of flexible sector coupling, realized through storage for heat and hydrogen, reduces the demand for electricity storage. This has a noticeable impact on the market potential for Carnot batteries. Regarding the profitability analysis, we simulate the German day-ahead market using AMIRIS identifying positive gross profits among different scenarios. We conclude that the gross profit of Carnot battery storage systems is highly impacted by their considerable size and their favourable market position. Our results indicate that profitability is strongly related to market power of the storage operator which is particularly pronounced when the profit maximization strategy is applied. Therefore, further research may focus on a more accurate simulation of the competition of flexibility options and on finding robust strategies for the storage operator considering its impact of market power. Additional revenue streams such as ancillary markets could also be integrated in upcoming studies. Additionally, we propose that future investigations should extend the scope to other regions worldwide, recognizing the potential variability in the energy landscape and market dynamics, thereby contributing to a more comprehensive understanding of Carnot battery applications on a global scale.

Author agreement statement

We declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We understand that the Corresponding Author, Felix Nitsch, is the sole contact for the Editorial process.

He is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

CRediT authorship contribution statement

Felix Nitsch: Writing – original draft, Visualization, Software, Methodology, Investigation, Conceptualization. **Manuel Wetzel:** Writing – original draft, Visualization, Software, Methodology, Investigation, Conceptualization. **Hans Christian Gils:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Kristina Nienhaus:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Overview of the model workflows

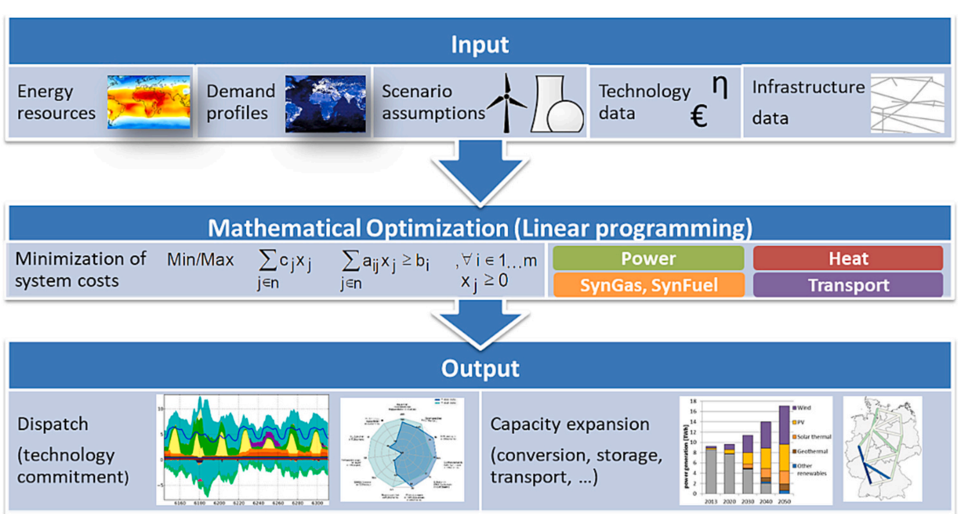

Fig. 8. Schematic overview of the REMix energy system model, from [58].

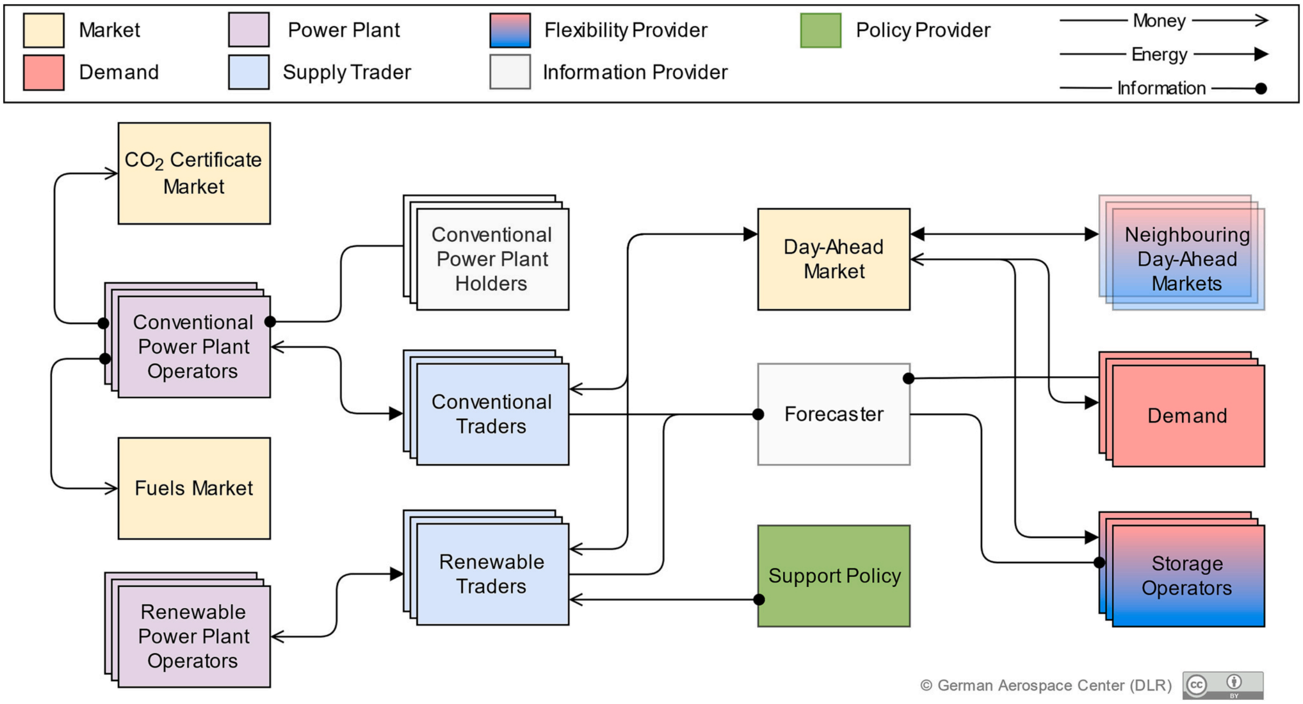

Fig. 9. Schematic overview of the electricity market model AMIRIS, see also [28].

Appendix B. Sensitivity analysis for the energy system design

As described in Section 2.3, further model calculations were carried out with REMix to examine how deviating assumptions on the composition of electricity generation and storage technology development affect the role of Carnot batteries in the cost-optimal system. This is realized by varying the cost assumptions for lithium-ion battery storage, P2G2P, photovoltaics and wind power plants. The additional assumptions used are based on values collected by the Danish Energy Agency [59] and the ranges of investment costs in 2050 mentioned therein. The resulting assumptions for battery storage costs are summarized in Table 3 and the assumptions for wind energy, photovoltaics and P2G2P in Table 4. The sensitivity analyses are carried out for the following three cases from the parameter study of technoeconomic assumptions on Carnot battery systems.

(1) 55 % round-trip efficiency, 35 €/kWh energy-specific costs and 150 €/kW power-specific costs
(2) 75 % round-trip efficiency, 35 €/kWh energy-specific costs and 400 €/kW power-specific costs
(3) 75 % round-trip efficiency, 75 €/kWh energy-specific costs and 150 €/kW power-specific cost

Table 3
Lithium-ion battery cost assumptions in the sensitivity analysis. The Base case values represent the assumptions used in the parametric study with the results presented in Section 3.1.

	base	battery++	battery+	battery0	battery-	battery–
Energy storage expansion cost (€/kWh)	75	46	78.5	111	143.5	176
Output capacity expansion cost (€/kW)	60	40	92.5	145	197.5	250

Table 4
Cost assumptions for wind energy, photovoltaics, electrolysis and methanation in the sensitivity analysis. If a field specifies no values the Base values are used. For all technologies fixed operational costs are scaled accordingly.

	base	p2g2p+	p2g2p-	pv + wind-	pv + wind+	pv-wind+
Electrolyzer expansion cost (€/kW)	350	150	500			
Methanizer expansion cost (€/kW)	800	450				
Photovoltaic expansion cost (€/kW)	518			250	250	
Onshore wind expansion cost (€/kW)	1173				800	800
Offshore wind expansion cost (€/kW)	1800				1640	1640

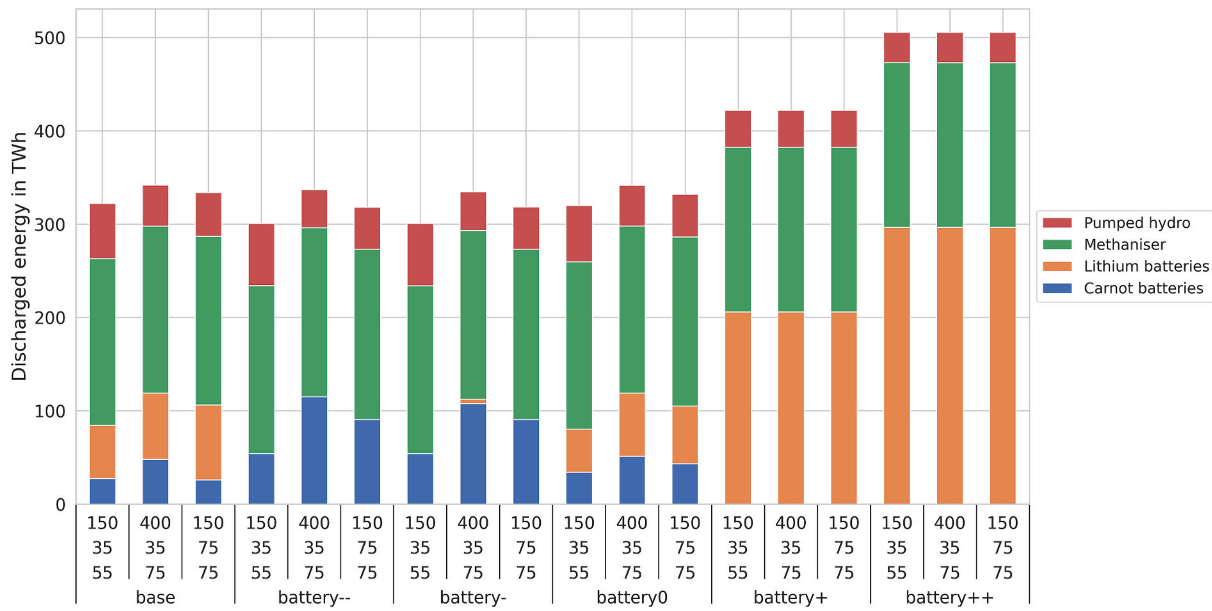

Fig. 10. Discharged energy across Europe (battery scenarios).

Varying the costs for lithium-ion batteries results in the expected effects, see Fig. 10. Thus, with higher battery costs in all three cases examined, there is almost complete substitution of lithium-ion batteries by Carnot batteries. The total capacity of the battery storage systems remains approximately constant. The effects are uniform for the three sets of assumptions analyzed for Carnot batteries. Assuming lower costs for lithium-ion storage systems, on the other hand, Carnot batteries are completely pushed out of the system and the total capacity of the storage systems is doubled or tripled. As no Carnot batteries are used anymore, the difference between the three model runs disappears.

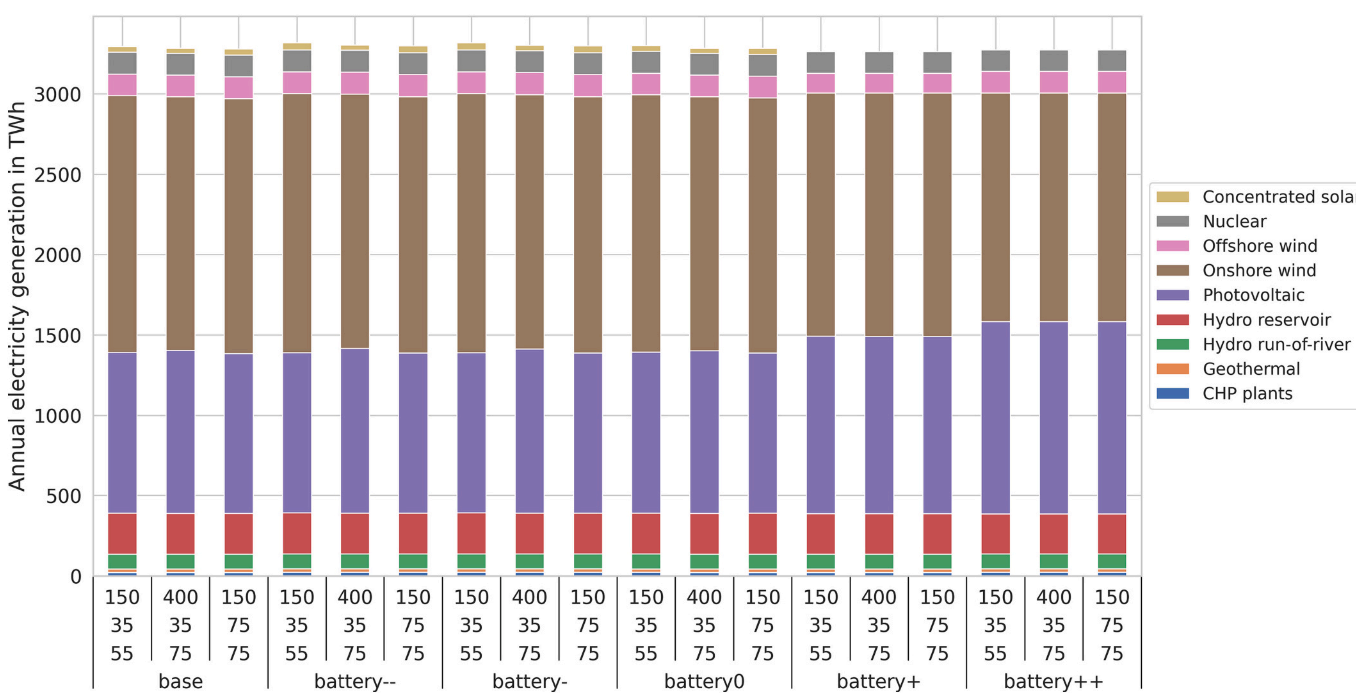

Fig. 11. Annual electricity generation across Europe (battery scenarios).

The variation in battery costs has only a minor impact on the power generation structure (Fig. 11). These are most evident in the case of lower battery costs, which lead to CSP and partly also onshore wind being replaced by PV. Higher battery costs, on the other hand, lead to a slight increase in total electricity production, as the use of Carnot batteries is associated with higher losses.

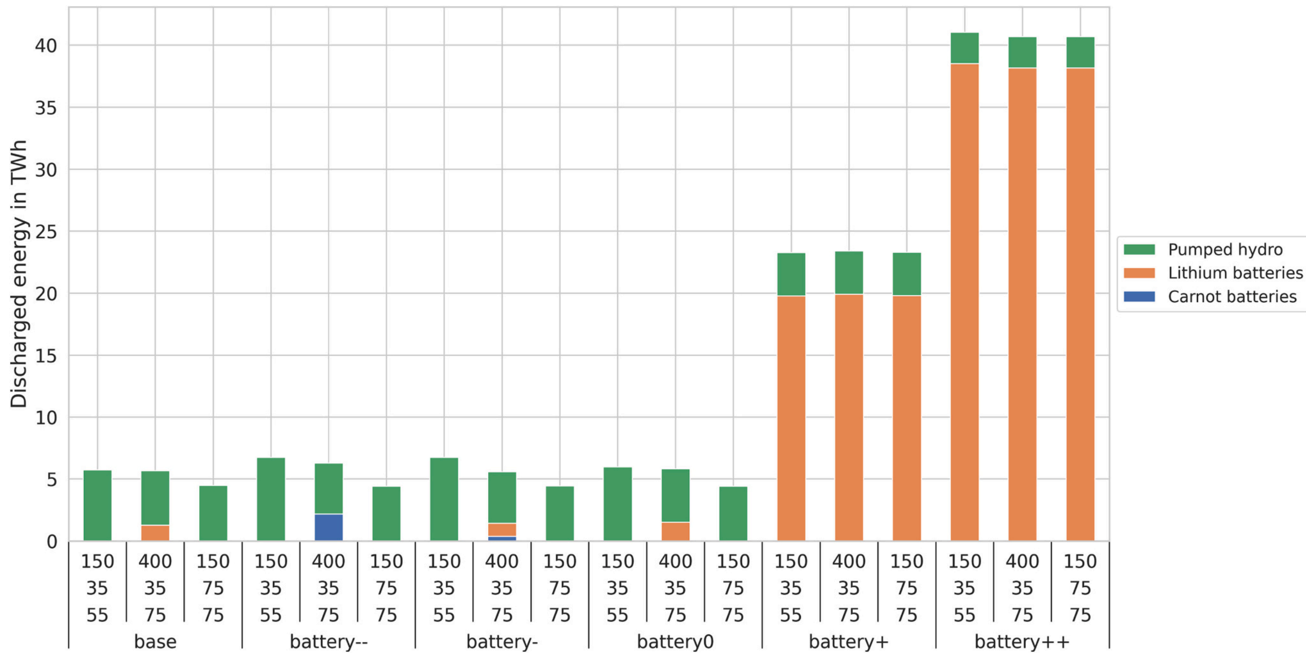

Fig. 12. Discharged energy across Germany (battery scenarios, without methanizer).

The described effect of the cost variations on the entire study area is essentially also confirmed for Germany. However, the importance of electricity storage is lower there due to the greater availability of other flexibility. This means that an increase in lithium-ion battery costs only has a very insignificant effect on the use of electricity storage (Fig. 12), although in case of a significant cost increase (battery–), lithium-ion batteries are replaced by Carnot batteries. A reduction in the cost of lithium-ion batteries, on the other hand, would mean that they would find a place in the German system and significantly increase the importance of electricity storage.

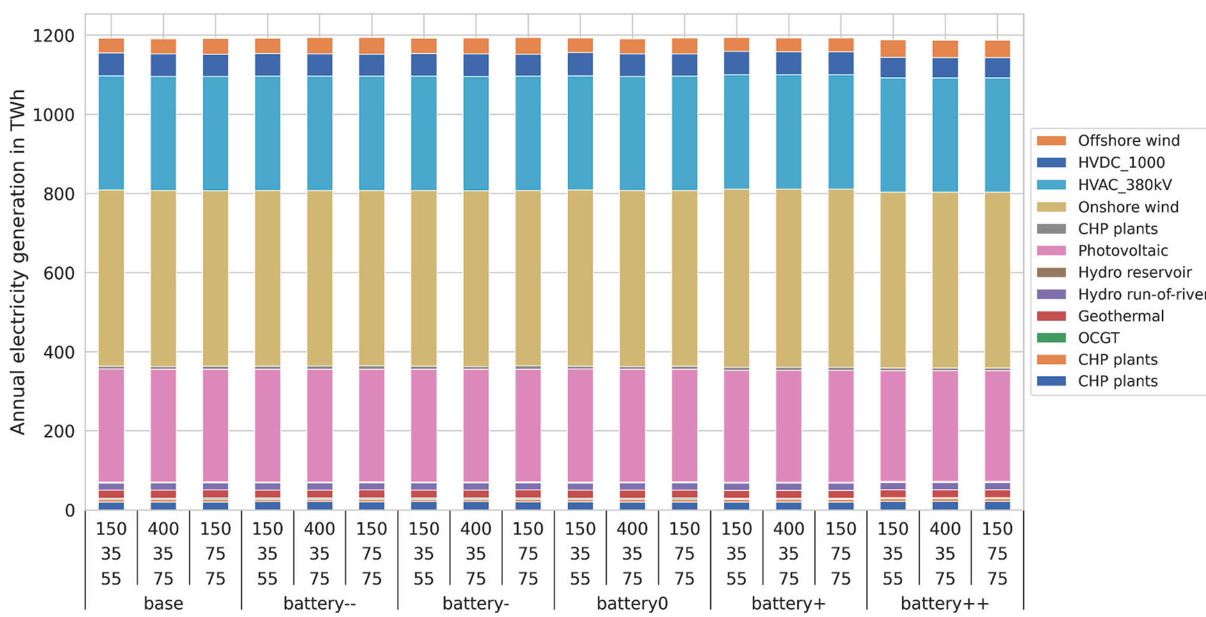

Fig. 13. Annual electricity generation in Germany (battery scenarios).

The analysis of electricity generation in Germany shows that the variation in lithium-ion battery storage costs only changes this very slightly (Fig. 13). The most relevant aspect is the slight decrease in total generation due to the reduction in renewable energy curtailment and storage losses in case of significantly cheaper chemical batteries (battery++).

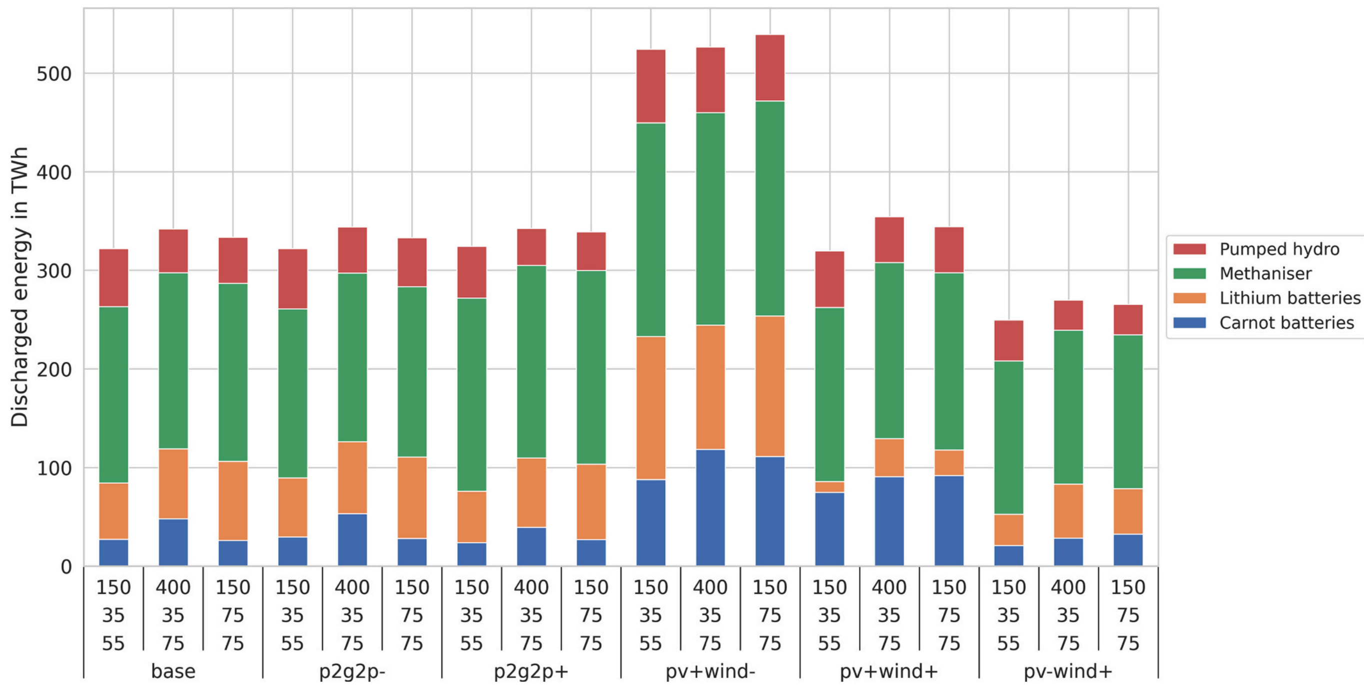

Fig. 14. Discharged energy across Europe (VRE scenarios).

The considered variations in the cost assumptions for the production and reconversion of synthetic methane only have a very weak effect on the results (Fig. 14). As the methanization plants are essentially used to cover gas demand in industry, cost changes have hardly any influence. This also applies to the other storage technologies analyzed. A different picture emerges when varying the costs of VRE technologies. Reduced PV costs significantly increase the contribution of this technology to electricity generation and push offshore wind in particular out of the system (Fig. 15). This results in a significantly higher storage requirement, which is covered disproportionately by Carnot batteries. Discharge from lithium-ion batteries also doubles. If both wind and PV costs are assumed to be lower, this has a particular impact on wind power generation, where offshore wind is replaced by onshore wind. This also results in a change in storage requirements. Although this hardly increases for the sum of lithium-ion and Carnot batteries, the latter can significantly increase their share. If a cost reduction is only assumed for wind, this again makes onshore wind generation in particular more attractive. This displaces offshore wind and PV in equal measure and also reduces the need for storage. However, lithium-ion batteries are also more affected here than Carnot batteries.

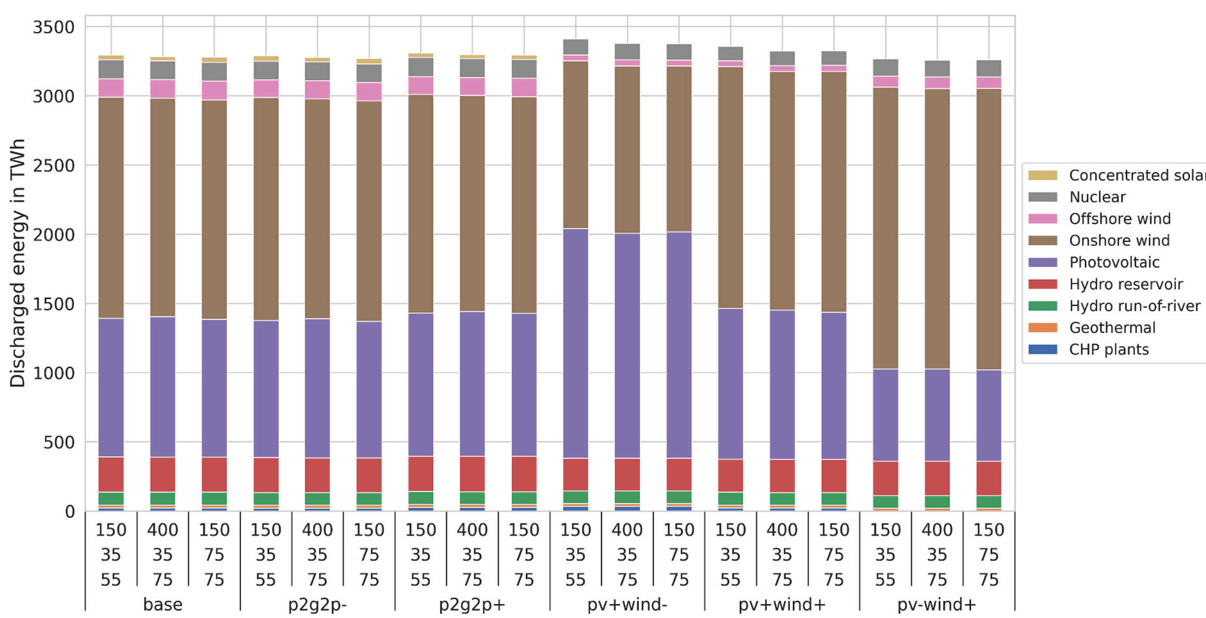

Fig. 15. Annual electricity generation across Europe (VRE scenarios).

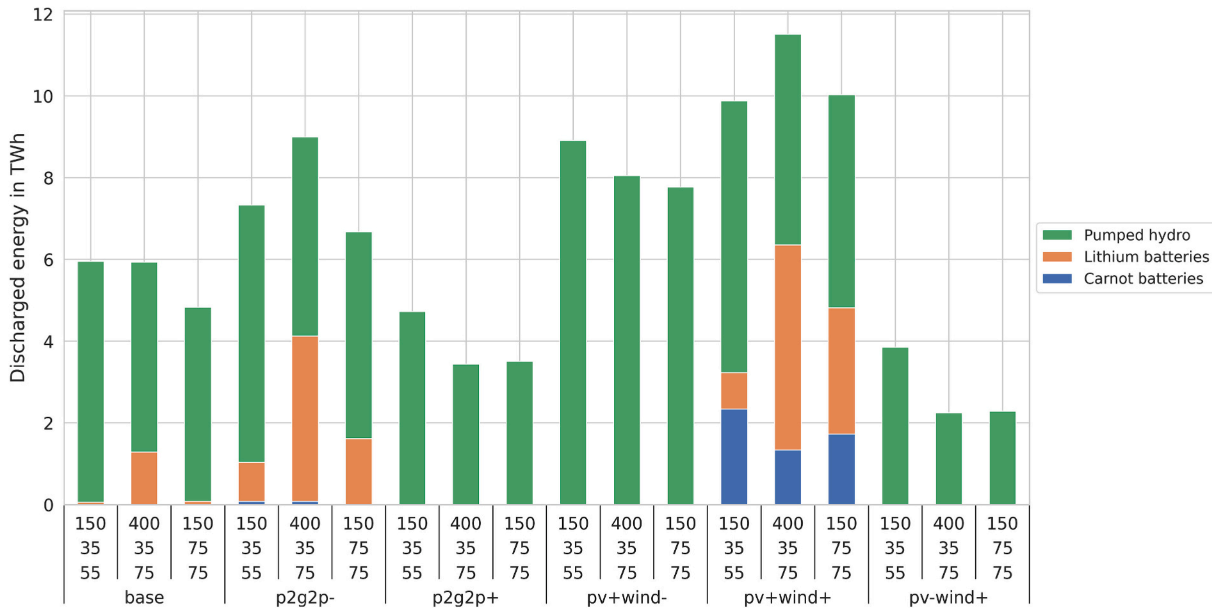

Fig. 16. Discharged energy across Germany (VRE scenarios, without methanizer).

A focused look at Germany reveals some further effects (Fig. 16). For example, the very low contribution of lithium-ion batteries in the *Base* case is significantly increased by higher costs for gas generation and reconversion, and Carnot batteries also enter the system to a very small extent. In the opposite case of lower costs, however, there is no longer any room for batteries. Lower PV costs significantly increase the use of pumped hydro storage, but battery storage is no longer part of the system. In the case of reduced wind power costs, batteries are again not part of the optimal solution, and the use of pumped storage is also reduced. At first glance, the result for the case of reduced costs for wind and photovoltaics is surprising. This leads to an even greater increase in the use of electricity storage than a cost reduction for photovoltaics alone. In addition, not only is the use of lithium-ion batteries increased here, but Carnot batteries are also used. This results from the increased use of photovoltaics and onshore wind, which are supplemented by different storage systems. In contrast, the use of offshore wind and flexible CHP plants is reduced (Fig. 17).

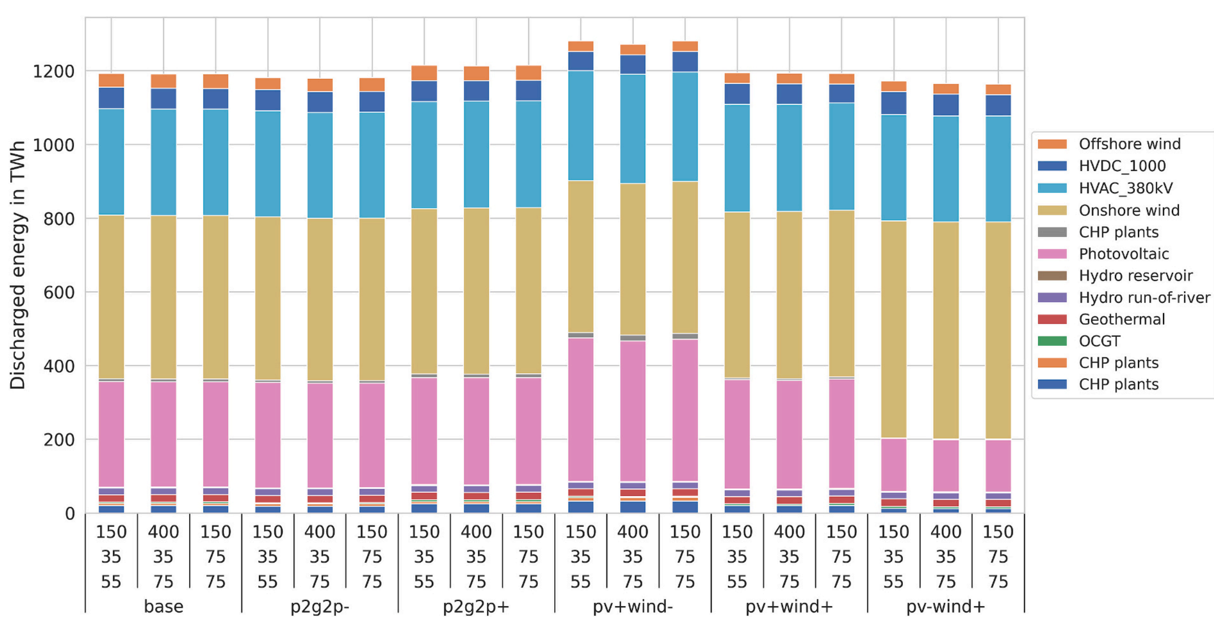

Fig. 17. Annual electricity generation in Germany (VRE scenarios).

Appendix C. Spatial distribution of Carnot batteries in Germany

In the case of Germany, the techno-economic targets for Carnot batteries need to be quite ambitious in order to arrive at relevant capacities. This effect is more prominent due to the sectoral representation with a detailed heating and gas sector. Both sectors allow for flexible demand via heat pumps, electric boilers and electrolysis, which in turn reduce the overall storage demand. In addition, due to the optimistic assumptions in the chosen techno-economic configuration lithium-ion batteries are almost completely pushed out of the system. As a result, in the *Base* case (Fig. 18a) Carnot batteries are only expanded in the Southern regions of Germany while with less flexible demand for electrolysis (Fig. 18b) and prevention of grid expansion (Fig. 18c) the overall demand for storage technologies increases and Carnot batteries are expanded in more model regions.

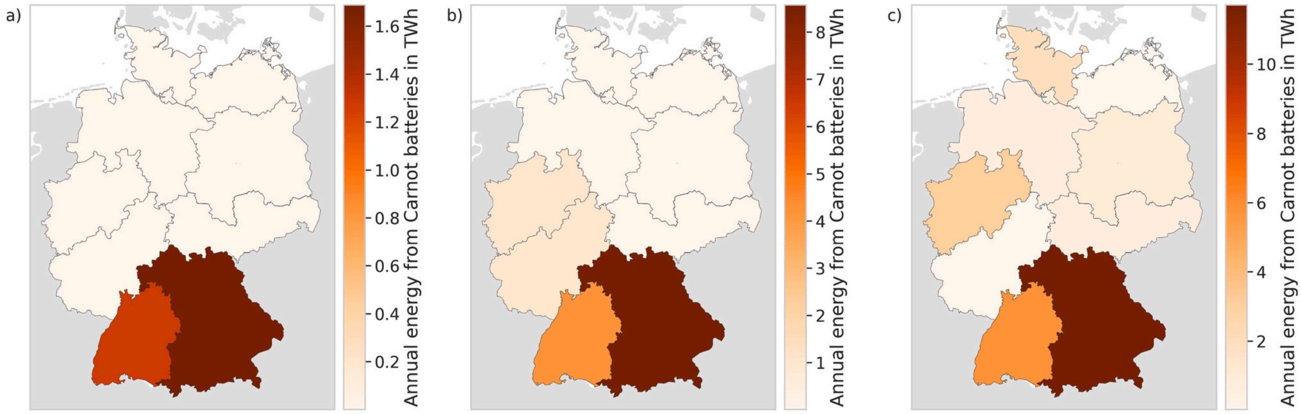

Fig. 18. Spatial distribution of annually provided energy from Carnot batteries for the three scenarios base (a), low flexibility electrolysis (b) and no additional grid expansion (c). Values are derived from the techno-economical configuration of 65 % round-trip efficiency, 20 €/kWh storage specific CAPEX and 150 €/kW power specific CAPEX.

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Glossary

ABM: Agent-based electricity market model
AMIRIS: ABM developed at the German Aerospace Center
CAPEX: Capital expenditure
E2P: Energy-to-power (ratio)
REMix: Framework for optimizing energy system models
VRE: Variable renewable energy