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Published in:
Energy

DOI (link to publication from Publisher):
10.1016/j.energy.2023.128837

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Sorknæs, P., Thellufsen, J. Z., Knobloch, K., Engelbrecht, K., & Yuan, M. (2023). Economic potentials of carnot batteries in 100% renewable energy systems. *Energy*, *282*, [128837].
https://doi.org/10.1016/j.energy.2023.128837

Energy 282 (2023) 128837

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Economic potentials of carnot batteries in 100% renewable energy systems

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A R T I C L E I N F O

Handling Editor: G Chicco

Keywords:
Carnot battery
Smart energy system
Energy storage
Renewable energy

A B S T R A C T

In 100% renewable energy systems, the requirements for flexibility will be greater than for traditional carbon-based energy systems. New technologies and system setups are needed to provide flexibility for balancing the system. Implementing electricity storages in the energy system could provide parts of the required flexible demand and production, though most of these storage solutions have been shown to have relatively high costs. So-called Carnot batteries have been shown to have a relatively lower cost than traditional batteries, but at a reduced electric efficiency. This paper investigates to what extent large-scale integration of Carnot batteries has a role in the transition to and the operation of 100% renewable energy systems. By implementing Carnot batteries in a 100% renewable energy scenario for Denmark, the energy system effects are identified. The results indicate that the potential economic benefit could be as high as 60.5–66.2 EUR/MWh$_e$ discharged, not including costs related to investment as well as operation and maintenance of the Carnot batteries. Thus, large-scale integration of Carnot batteries must perform below this economic threshold to be economic relevant. Existing concepts for stand-alone Carnot batteries are not able to achieve these costs today, therefore solutions for cost reductions should be investigated.

1. Introduction

With targets to reduce global carbon emissions, energy systems are moving towards more and more carbon-neutral energy production dominated by a rapid expansion of renewable energy [1]. With the transition from dispatchable fossil fuel-based thermal plants to an energy mix based on renewable energy, the primary flexibility of the system will no longer be based on thermal plants Instead the rest of the energy system has to be more flexible to allow for a low-cost and energy-efficient transition [2]. This includes the use of flexible demand [3], sector coupling technologies [4], and utilization of energy storages. Regarding storages, especially thermal, gas and fuel storages can provide low-cost options compared to electricity storage [2]. To identify the possible use of different flexibility measures, it is important that the transition of the energy system is considered holistically. Approaching the energy system transition holistically is often referred to as the Smart Energy System approach, where all energy sectors and demands are included in the analysis [2].

In the transition to 100% renewable using mainly variable renewable energy sources (RES), such as wind power and photovoltaics, the capacities for the variable RES have to be scaled so that production most of the time will exceed the mostly inflexible electricity demand of today's energy system [5,6]. Having such large capacities of variable RES in the electricity system means that to ensure flexibility, sector coupling between the electricity system and other energy sectors becomes more important to utilize the excess electricity efficiently. For instance, flexibility in the form of Power-to-X solutions e.g., for fuel production [7,8], charging (and discharging) of electric vehicles [9,10], and production of heat and cooling e.g., to be used and stored in district heating [11,12] and cooling systems [13,14]. However, even with a large capacity of variable RES there will still be times when variable RES cannot cover the inflexible electricity demands. Currently, a number of solutions exists for these periods, which are restricted geographically such as dammed hydropower, limited by the availability of resources such as biomass, or are very expensive to implement. The use of pumped and dammed hydropower to provide system flexibility requires the right topology, and as such cannot necessarily be a solution everywhere. Biogas and other green gases can be used in gas turbines [15] but these resources are limited based on the amount of sustainable available biomass [16,17]. Finally, e-fuels, battery storages and similar solutions can provide the flexibility by storing the energy from periods with large amounts of variable RES production to periods with low production, but these solutions tend to be expensive [18,19]. Finally, countries can assist each

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https://doi.org/10.1016/j.energy.2023.128837
Received 6 March 2023; Received in revised form 18 August 2023; Accepted 20 August 2023
Available online 21 August 2023

Abbreviations

CAPEX	Capital expenditure
CEEP	Critical excess electricity production
CHP	Combined heat and power
LAES	Liquid air energy storage
LCOS	Levelized cost of storage
RES	Renewable energy sources
RTE	Round-trip efficiency
O&M	Operation and maintenance
OPEX	Operation costs
PTES	Pumped thermal energy storage
PV	Photovoltaics

other through interconnection [20], which can balance variable RES production over larger geographic areas and national borders.

When identifying the flexibility of future renewable energy systems, it is key to identify relevant technologies to ensure sufficient security and flexibility. The given potentials are not equal across all countries, so different technologies must play a role. In this context, the potential of Carnot batteries [21] should be investigated, as these might prove to provide a relatively low-cost solution better suited in locations without access to pumped/dammed hydro power and sustainable biogas.

1.1. Carnot batteries

Carnot batteries are thermo-mechanical energy storage technologies that store electricity in the form of thermal energy and are characterized by electricity as their main output [22]. The temperature difference between two thermal reservoirs created during the charge process drives a power cycle during discharge. Consequently, Carnot batteries are typically classified by the most prominent thermodynamic cycle proposed for the conversion between electricity and heat [21,23]. As this classification indicates, the term Carnot battery encompasses concepts such as liquid air energy storages (LAES) and Brayton or Rankine based pumped thermal energy storages (PTES); but also, Lamm-Honigmann storages and hybrid concepts such as systems based on integrated resistive heating with power cycles. As such, Carnot batteries cover a large range of different technologies.

Regarding their role in the energy system, a key feature of Carnot batteries is independent sizing of power and capacity, allowing a broad range of applications within the electric grid. For example arbitrage business, ancillary services, or peak shaving [21]. Additionally, the readily available hot and cold storages are unique features of Carnot batteries enabling multi-energy flexibility through the external use and integration of hot and cold recycle streams. According to a recent review from Liang et al. [22], most component-level challenges are related to the expansion/compression machines employed in Carnot batteries, demand for reversible machines and two-phase operability. In general, PTES (both Rankine and Brayton) are characterized by higher round-trip efficiencies (RTEs) of 45–60 and 52–70%, respectively, compared to 40–60% from LAES [21]. Nevertheless, LAES comes with the highest mean power output and lowest power-specific costs, making it highly suitable for large-scale applications [21]. Even though recent Carnot battery demonstration plants are showing net RTEs down to 11.3% [24], Carnot batteries still appear promising for storage durations between those of batteries (<4 h) and hydrogen (>150 h) despite their relatively low RTE, as demonstrated by Vecchi et al. [25] for Carnot batteries with conservative RTEs of 24–28%.

Whereas the potential thermal integration of Carnot batteries is inherently coupled to local boundary conditions, national scenarios on grid-level are inevitably relevant for the investigation of Carnot batteries, as the production and use of electricity is not only a local matter but also a national and international matter. Nevertheless, only a marginal share of literature addresses that. Martinek et al. identifies full-load discharge capacities of seven and 16 h for a Brayton based Carnot battery in photovoltaics- (PV) and wind-dominated scenarios, respectively, investigated for six hypothetical near-future grid scenarios in the US [26].

Furthermore, an increasing amount of work targets the integration of thermal storages in power plants, technically creating a Carnot battery and also referred to as thermal storage power plants [27]. With large differences in the amount of reused equipment, this emerging research direction covers everything from pure flexibility improvements of power plants [28] to the conversion of small- or large-scale power plants as well as newly constructed power plants based on the Carnot battery principle. Whereas Geyer and Giuliano investigate existing large-scale coal-fired power plants [29], Basta et al. estimate levelized cost of storage (LCOS) between 35 and 291 EUR/MWh$_e$ for a 5-h storage system in a coal-fired combined heat and power (CHP) plant up to 50 MW$_e$, depending on electricity and heat prices as well as the operating regime [30]. Liu and Trieb state that thermal storage power plants with their intrinsic Carnot battery are an effective hedge against fuel market price escalation and CO_2 cost additions and demonstrate that by comparing its cost to four kinds of conventional power plants [31]. On energy system level, converting CHP plants to Carnot batteries indicates the opportunity to avoid large amounts of curtailment and fuel consumption already in the current energy system, according to Gong and Ottermo [32]. In their study for the Swedish grid, 53% of the curtailment from wind and solar as well as about 21% of the fuel consumption are avoided by converting CHP plants with a total installed capacity of 3528 MW.

Overall, it can be concluded that a) stand-alone Carnot batteries are rarely investigated from an energy system perspective even though inherently relevant, and b) the overall agreement that Carnot batteries promise a stable LCOS against CO_2 and fuel price variations collides with the fact that this potential has never been quantified and subsequently assessed. In that context, especially the lack of knowledge about how fundamental Carnot battery variables such as (dis-)charge capacities, RTEs and storage capacities influence this potential is striking.

1.2. Novelty

Carnot batteries can provide a relatively low-cost solution not limited by geography and resources. The current research on Carnot batteries focuses on the performance of the technology in very limited settings. Thus, there is no research on its potential in a full Smart Energy System context, where competition with other flexibility technologies also is considered. This paper investigates the economic potential of Carnot batteries in such a setting, investigating whether the lower costs of Carnot batteries are competitive. The objective of the paper is to assess the energy system effects of different storage setups and assess the techno-economic parameters that a future Carnot battery must achieve to be competitive in a Smart Energy System dominated by production from variable RES. The potential assessed in the study only relates to the role of charging and discharging electricity, and therefore does not consider potential benefits of linking with district heating systems and utilization for steam and high temperature demands in industry.

2. Methods

The method section describes three main topics in order to analyze the economic potential of Carnot batteries in a future renewable energy system. First the section covers the layout of the future 100% renewable energy system scenario used for this study. The energy system is a fully decarbonized Danish energy system scenario based on 100% renewable energy, following the Smart Energy Systems principles [1]. The second topic is the energy system analysis tool used, EnergyPLAN, in which different Carnot battery setups are modelled into the 100% renewable energy system scenario. The final topic is the method for how to model

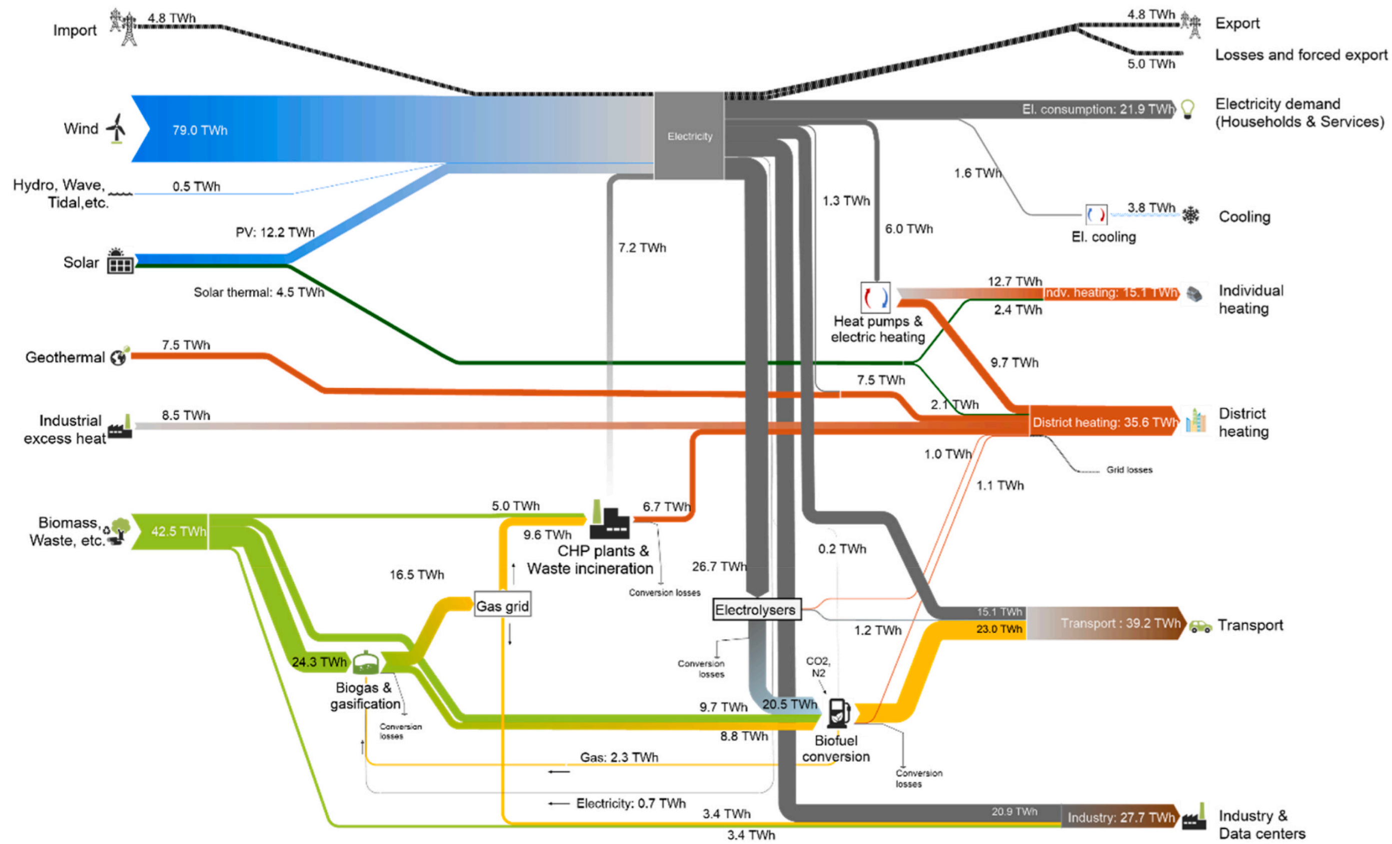

Fig. 1. Sankey diagram for the IDAs Climate Response 2045 scenario for Denmark [5].

and include Carnot batteries in EnergyPLAN as well as the simulation approaches and the Carnot battery setups tested. The goal of this approach is to identify the operation of the Carnot battery in the context of the entire energy system, with the goal of testing several input variables, including charge and discharge capacities, RTEs, and storage capacities. Together, this allows for an evaluation of the economic potential of the implementation of Carnot batteries and can serve as a measuring stick when developing the actual technology.

2.1. Scenario simulated

As an example of a future 100% renewable energy system, the scenario IDAs Climate Response 2045 is used. IDAs Climate Response 2045 is a scenario that shows a possible future Danish energy system that is based 100% on renewable energy while utilizing a sustainable amount of biomass [5,16]. Fig. 1 shows a Sankey diagram of the energy system scenario, detailing the use of primary energy through conversion to each individual end use demand. Besides being 100% renewable, the scenario goes for carbon neutrality in the Danish society, with a potential to include carbon sinks. Thus, the model does not include carbon prices as the overall greenhouse gas emissions from the energy system is zero. The scenario includes electricity, heating, cooling, transport, and process heating demands, so that all energy demands are included and decarbonized. It achieves this mainly by installing 14 GW offshore wind power, 5 GW onshore wind power and 10 GW PV that delivers nearly 70% of the total primary energy consumption of the energy system scenario. By sector coupling, the renewable energy is utilized across all energy sectors with electricity being converted to heat, fuels, and used in industry and transport. To achieve flexibility in the system while covering energy demands in periods with low variable RES production a total of 4.8 GW_e flexible gas-fired CHP and power plants are installed in the form of a mix of combined- and simple-cycle gas turbines. In Fig. 1 these are part of the CHP plants and waste incineration category. These are only used for periods with low variable RES production compared with the inflexible electricity demand, and as such, only have around 1000 full load hours per year. The power plants operate alongside 6 GW of electricity transmission capacity, a capacity similar to the total Danish transmission grid to Sweden, Norway, and Germany in 2020. To utilize more energy in periods with large production from variable RES, flexible demands are included, including 4.8 GW of electrolysis capacity utilized in Power-to-X facilities to produce liquid and gaseous fuels, as well as the inclusion of heat pumps in individual buildings and district heating, as well as flexible charging of electric vehicles. All these allows for installing sufficient variable RES capacity in a way to cover most of the hours of the classical electricity demand. It is within this scenario that Carnot batteries are tested.

2.2. Energy system modelling tool

EnergyPLAN [33,34] is a holistic energy system analyses tool for modelling and simulating energy systems of different scales, e.g. national such as Denmark [5] and Austria [12], regional such as Beijing-Hebei-Tianjin [35,36] and Gran Canaria [37], and city such as Aalborg [38] and Cuenca-Azuay [39]. EnergyPLAN chronologically simulates one leap-year of operation of the modelled energy system by calculating energy flows while utilizing sector-coupling to connect technologies and energy storages. EnergyPLAN includes five different energy demands: electricity, heating, cooling, transport, and industrial process heating. It aims to meet these energy demands in each hour of the simulated year by utilizing the energy conversion technologies, energy storages, and import of electricity and fuels. The different components are aggregated into their general categories in EnergyPLAN. An overview of the different energy resources, energy conversion technologies, energy storages, energy demands, and their interconnections can be seen in Fig. 2.

EnergyPLAN has two different operational strategies for the

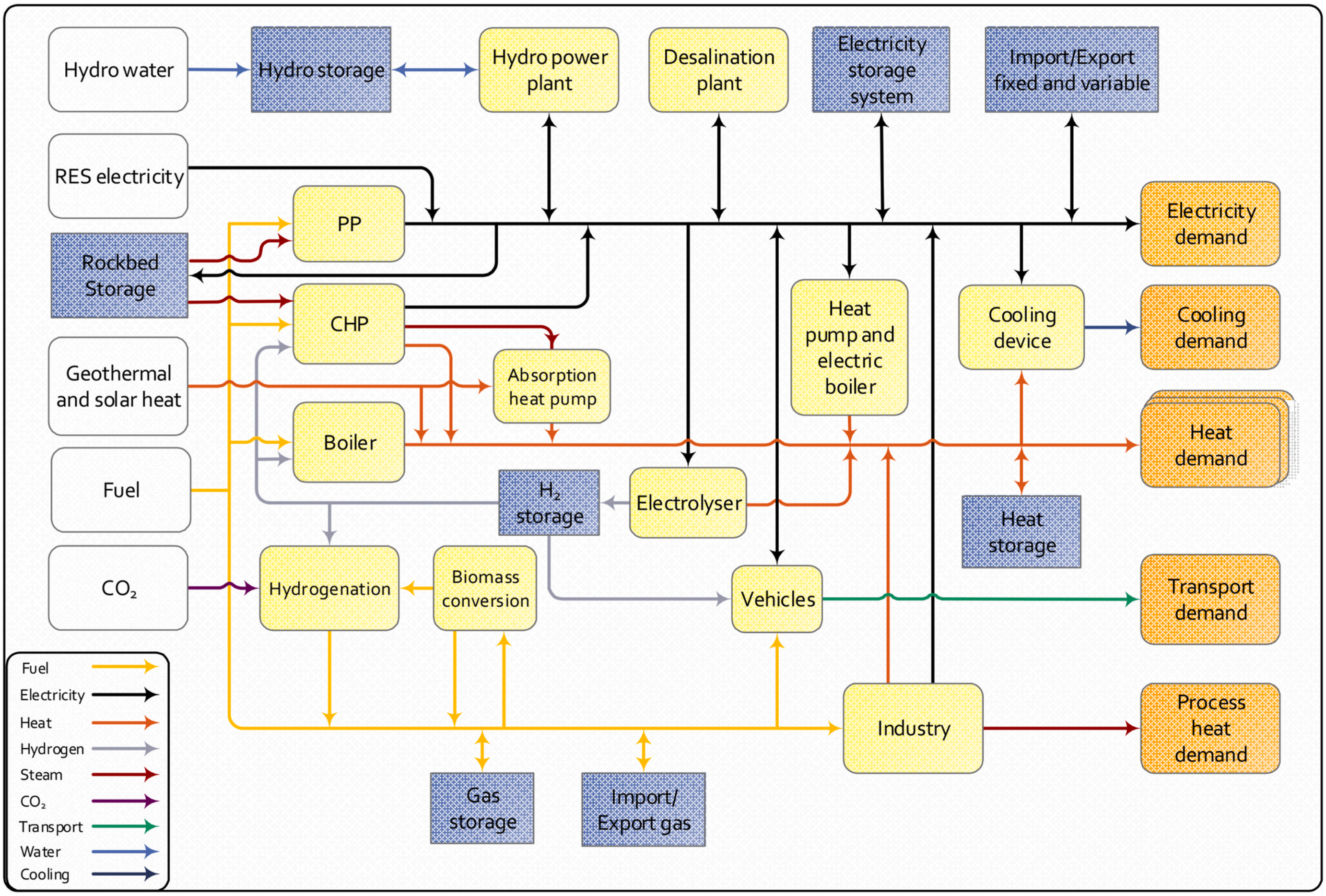

Fig. 2. Overview of energy resources, energy conversion technologies, energy storages, energy demands, and their interconnections in EnergyPLAN. [34].

simulation, Technical Simulation and Market Economic Simulation. The Technical Simulation operates the different units based on a preset order of activation with the goal of providing the lowest fuel consumption for the energy system. The Market Economic Simulation strategy operates the different units based on the short-term marginal costs to provide the best business economic operation of each unit. In this study, the Technical Simulation strategy has been utilized for all simulations. The consequence of this choice is that EnergyPLAN will optimize storages to reduce power plant production, by storing otherwise curtailed electricity production from wind power and PV, known as critical excess electricity production (CEEP) in EnergyPLAN. Thus, by introducing Carnot batteries as electricity-to-electricity storages in the used energy system scenario in EnergyPLAN, predominantly the use of flexible gas-fired power stations is expected to be reduced.

2.3. *Modelling and simulation of carnot batteries*

In the paper, Carnot batteries are modelled as stand-alone batteries, meaning that they can be defined as electricity charge capacity, storage capacity, electricity discharge capacity, and an average RTE. As such, the study does not include potential heat output for district heating or industrial purposes from Carnot batteries. Also, the modelling only includes flows of energy, and do not include mass flows, etc. Due to the large array of potential different technical setups of Carnot batteries, as described in the Introduction, different principal setups are tested, to ensure a wide range of setups are tested. E.g., RTEs have been reported from down to 11.3% in recent demonstrations up to around 70% for PTES in research papers. Also, the flexibility in capacities to charge, discharge and storage of different Carnot battery configurations makes it relevant to investigate how different capacities affect the results. As this study is investigating relatively large-scale integration of Carnot batteries, suitable large capacities are investigated. Specifically, at least 0.5 GW_e charge capacity is investigated, which corresponds to around 10% of the installed capacity of flexible gas-fired CHP and power plants in the used scenario. Due to the relatively large losses of energy in Carnot batteries, the discharge capacity will be set relative to the input capacity, and never above the input capacity. As Carnot batteries are expected to be used for storage within a maximum of a few weeks, the maximum storage capacity tested is 7 days of full charging. The setups include variations to electricity charge capacity, electricity discharge capacity, storage capacity, and RTE. The different variations made are.

- 4 different electric charge capacities: 0.5 GW_e, 1 GW_e, 1.5 GW_e and 2 GW_e.
- 8 different electric discharge capacities: Interval of 12.5% up until 100% of charge capacity.
- 7 different electric storage capacity: 1–7 days of charge capacity.
- 5 different levels of RTEs incl. Self-discharge: 15%, 30%, 45%, 60%, and 75%.

Each of these variations are tested with each combination of the other, resulting in a total of 1120 different technical setups of the Carnot batteries being tested in the simulations. In a specific investment situation, some of the technical setups might be less relevant than others, e.g., 7 days of storage capacity with 15% RTE. However, the used variations are expected to cover all different potential setups of Carnot batteries. Thus, each of these combinations are not connected to a specific type of Carnot battery, but the ranges tested will ensure that all potential

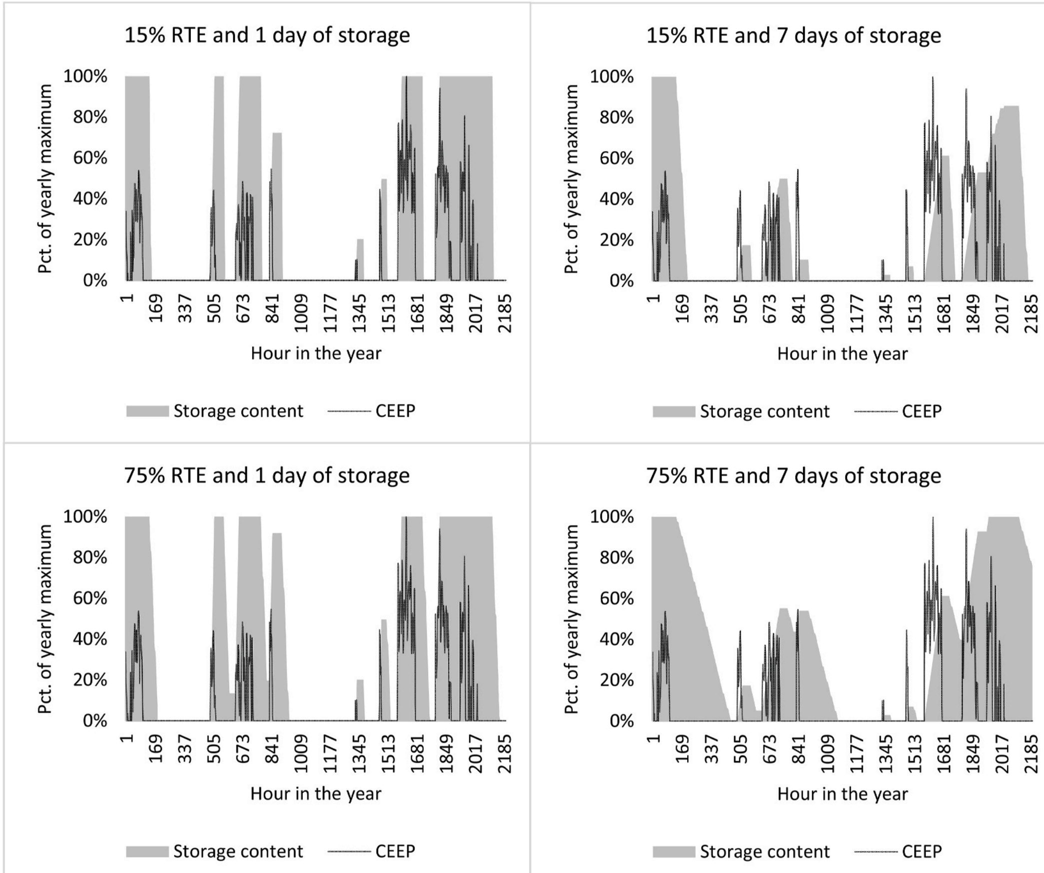

Fig. 3. Storage content and CEEP in each hour in January, February, and March for four different variations. In all the graphs the Carnot battery charge capacity is 1 GW_e and the discharge is 0.5 GW_e.

types are included in the analyses. In EnergyPLAN the RTE is set by the discharge efficiency.

As to highlight the energy system effects and remove the competition with flexible technologies outside Denmark, for instance dammed hydropower in Norway, the electric transmission capacity is removed from IDAs Climate Response 2045. To make sure that the electricity system is still in balance, the power plant capacity is increased by 6 GW, the same size as the removed transmission capacity. As this extra power plant capacity is used for backup, it is assumed to be simple-cycle gas turbines due to these having a relative low capital expenditure (CAPEX). This change also means that the gas consumption is increased in the scenario, compared to the scenario data shown in section 2.1, though as the focus here is on the variation between scenarios, it does not affect the results of the analyses shown in this paper.

Due to the simulation strategy used in EnergyPLAN as described in section 2.2, the Carnot batteries are mainly charged to reduce the use of power plants (not CHPs) at a later period of the year. The cost reduction is therefore mainly dependent on the assumed cost for gas, as in the used scenario the power plants are gas-fired. In IDAs Climate Response 2045 a gas price of 7.8 EUR/GJ excl. Transport costs was used based on a price projection from the Danish Energy Agency. However, since the gas used in the power plants comes from biogas facilities within Denmark, it could be argued that the cost for gas should reflect this, which would correspond to a gas price of around 9.2 EUR/GJ [40]. However, gas prices could also be even higher as gas is traded internationally and the international market price could be set by more expensive ways of producing gas, with electro-methane showing the highest cost around 18.1 EUR/GJ [40]. Thus, in the paper, a gas price of 9.2 EUR/GJ incl. Transport costs has been used, in line with the cost projections for biogas in Denmark. A higher gas price would result in higher cost reductions by Carnot batteries. Reducing the operation of the power plants will also reduce the costs related to variable operation and maintenance (O&M) of the power plants, though in the IDAs Climate Response 2045 scenario the variable O&M is only 2.92 EUR/MWh_e and with a gas price of 9.2 EUR/GJ and an efficiency of 45% this cost only corresponds to around 4% of the short-term marginal cost, with the rest being fuel costs.

When adding Carnot batteries to the IDAs Climate Response 2045 EnergyPLAN model, no costs are added for the Carnot batteries. This means that the results indicate the maximum economic potential of the Carnot battery, which in this study is interpreted as the maximum cost the Carnot batteries can have before they become an extra cost for the energy system. As this result is the total expenditure divided by the amount of electrical energy discharged from the storage during its lifetime ($MWh_{e,dis}$), it corresponds to the increasingly used LCOS. As shown in Equation (1), the numerator consists of the CAPEX as well as the annual costs A_t of the storage system at each time t over the storage lifetime n, discounted with the interest rate i. Also discounted, the denominator consists of the annual energy outputs W_{out}.

$$LCOS = \frac{CAPEX + \sum_{t=1}^{t=n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{t=n} \frac{W_{out}}{(1+i)^t}} \tag{1}$$

The annual costs A_t, described with Equation (2), are the sum of operation costs $OPEX_t$, capital reinvestments $CAPEX_{re,t}$, the costs for electricity being the product of electricity price c_{el} and annual input W_{in} as well as a recovery value R for the end of the lifetime.

$$A_t = OPEX_t + CAPEX_{re,t} + c_{el} W_{in} - R_t \tag{2}$$

The cost reductions from the simulations do not include potential gains from flexibility that the Carnot batteries can deliver within each

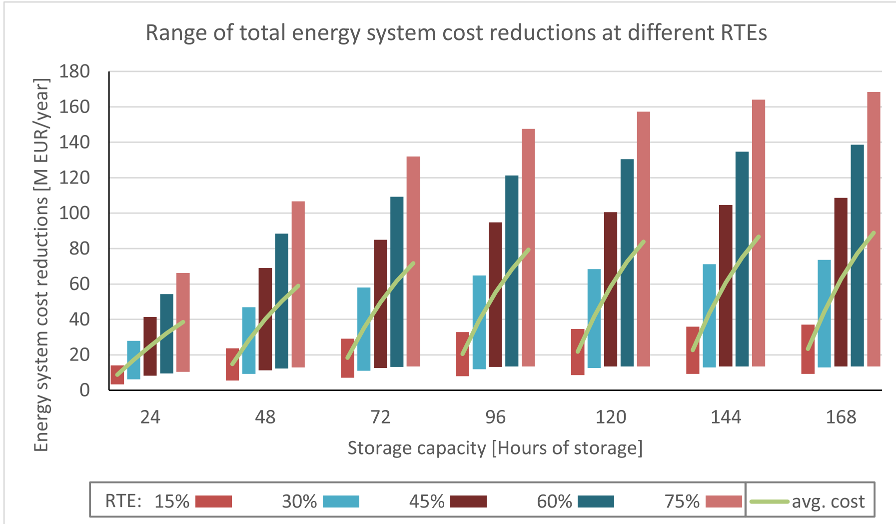

Fig. 4. Ranges of total annual cost reductions of the energy system at different levels of RTE and storage capacity in hours of charge capacity. The ranges cover different capacities for charge and discharge. Average is the average of all setups within each range. Investment and O&M costs for Carnot batteries are not included.

hour, e.g. frequency restoration. However, as described in the Introduction and section 2.1 a lot of new flexible technologies are assumed to also enter the electricity system when going to 100% renewable energy, meaning that there likely will be many other technologies that can also supply these balancing and reserve needs for the grid, and these services tend to be relative small volumes. Hence basing the long-term economic gains of a large-scale integration of Carnot batteries on the income from such services would be quite uncertain, and therefore it is not included here.

3. Results

In this section the results of the energy system analyses in EnergyPLAN are presented. First, examples of the hourly operation of the Carnot batteries as simulated in EnergyPLAN are shown. Afterwards, the energy system analyses results are presented. As a total of 1120 different setups are tested, the results are mainly presented as ranges. The results focus on the energy system cost effects and on the yearly operational characteristics of the Carnot batteries. The main results from all simulations are attached as supplementary material. The used scenario EnergyPLAN file, as described in section 2.1, can be downloaded from Ref. [41].

3.1. Examples of hourly operation

As to exemplify the hourly operation of different Carnot battery

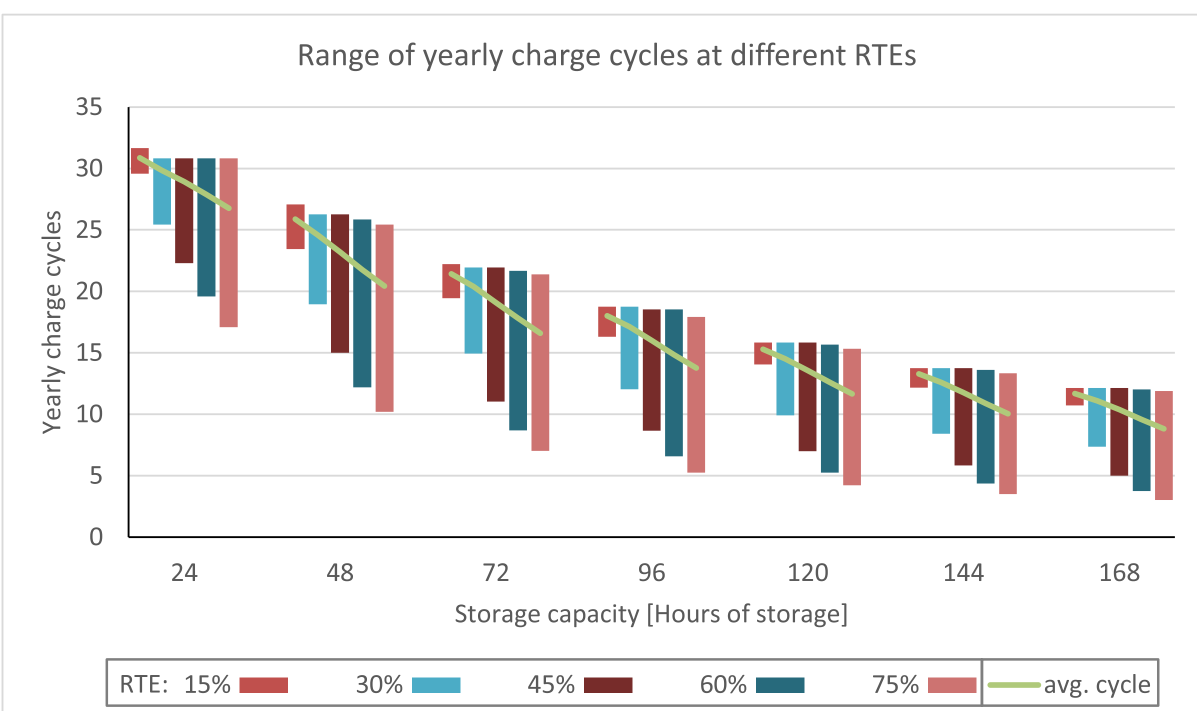

Fig. 5. Ranges of number of yearly charge cycles that the Carnot batteries experience at different levels of RTE and storage capacity in hours of charge capacity. The ranges cover different capacities for charge and discharge. Average is the average of all setups within each range.

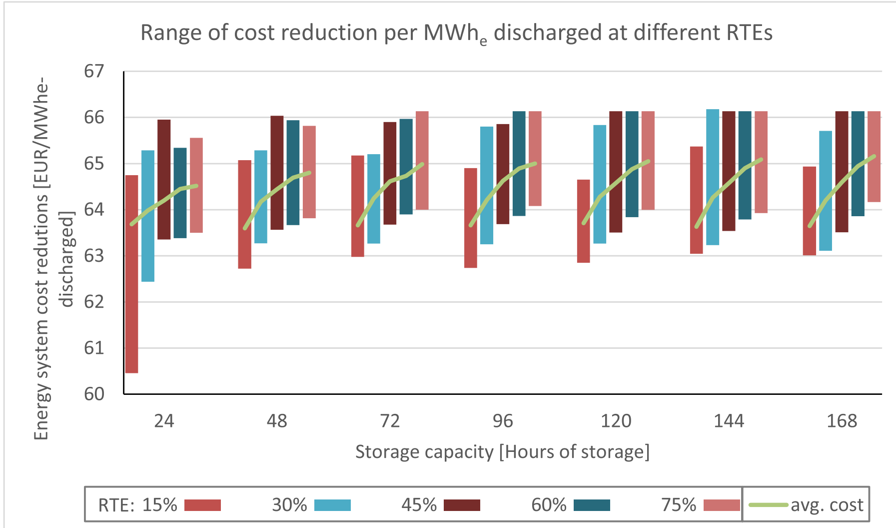

Fig. 6. Ranges of energy system cost reductions per $MWh_{e,dis}$ from the Carnot batteries at different levels of RTE and storage capacity in hours of charge capacity. The ranges cover different capacities for charge and discharge. Average is the average of all setups within each range. Investment and O&M costs for Carnot batteries are not included.

variations, Fig. 3 shows the hourly storage content for four different variations of the Carnot battery in the first three months of the year. The content is presented as percentage of storage capacity. All four Carnot battery variations have charge and discharge capacities of 1 GW_e and 0.5 GW_e, respectively, while the RTE is either 15% or 75% and the storage capacity is either 1 day or 7 days of storage (based on the corresponding charge capacity). The hourly storage content is shown alongside the hourly CEEP in the scenario without any Carnot battery, as to show when there is a potential to store otherwise curtailed electricity production from wind power and PV. As such, the CEEP is the same in all the four graphs and only the storage content is changing with variations to the Carnot battery. As seen in the figures the batteries charge when there is a CEEP in the system and discharge outside these periods as well as in periods where power plants are operating (not shown in the graphs). In case the storage is full, the storage cannot utilize the CEEP. For lower RTE and lower storage capacity, the storage is discharged faster, which enables an earlier recharging, given that there is CEEP available for charging. Based on these four examples for the first 3 months of the year, indicate that the RTE affects the storage operation more significantly for larger storage capacities, for the selected charge and discharge capacities.

3.2. Results of the energy system analyses

Fig. 4 shows the range of total energy system cost reduction that the Carnot batteries provides at different RTEs and storage capacities. Predominantly the cost reductions are tied to lower usages of power stations running on gas. The storage capacity is expressed in hours of storage in relation to the charge capacity. The range covers the different tested charge capacities and discharge capacities, and each bar covers 32 different Carnot battery setups. The results show that higher RTE and storage capacities increase the total cost reductions, though the size of the ranges increases especially with the increase of storage capacity. This means that in some cases, the cost reduction with higher RTE is similar as with a lower RTE when they have equal storage capacity. This especially occur for setups with low charge capacity and discharge capacity. E.g., the lowest total cost reduction in the setup with 168 h of storage and 75% RTE occur with a charge capacity of 0.5 GW and discharge capacity 12.5% of that charge capacity. It is also clear from the figure that there is a diminishing reduction in total energy system costs when increasing the storage size. For instance, when going from 24 h of storage to 48 h of storage, the result shows nearly a doubling of the cost reduction, but going from 144 to 168 h only provides a smaller reduction in total energy system costs.

Fig. 5 shows the ranges for the yearly charge cycles for the different RTEs and storage capacities. The charge cycles are here defined as the yearly electricity used for charging divided by the installed storage capacity. The results show that the yearly charge cycles are between 3 and 32. Thus, as the storage capacity increases the yearly charge cycles decrease, as it takes more energy to charge the storage. Generally, it can also be seen that a low RTE provides more yearly charge cycles, as the batteries will discharge the stored energy more quickly due to larger storage losses, allowing them to be sooner available for charge, as also illustrated by the four examples shown in Fig. 3. In the simulations charging generally occurs at over 90% of the installed charge capacity for all setups. The charging happens in around 10–20% of the hours of the year, with setups with higher storage capacities and lower relative charge capacity tending to charge in more hours of the year. Discharging generally occurs at a lower capacity, normally above 70% of the installed discharge capacity though down to around 50% in the scenarios with the highest discharge capacities. Discharging occurs in around 5–35% of the hours of the year, with setups with low RTEs, high discharge capacity, and low storage capacities operating in fewest hours. Setups with the lowest relative discharge capacity, largest storage capacities, and highest RTE show the highest number of hours of discharge. In the simulations the storage is full around 5–35% of the year. Setups with a low storage capacity and relatively large difference between charge and discharge capacities have the most hours with the storage full, and vice versa. The storage is empty in 5–40% of the year. Setups with low RTEs and small difference between charge and discharge capacities have the most hours of the year with the storage emptied, and vice versa.

Fig. 6 shows the range of energy system cost reductions per average $MWh_{e,dis}$ to the grid at different RTEs and storage capacities. As also described in section 2.3, this reduction is the same as the LCOS for the Carnot batteries, as it includes all expenditure over the full lifetime of a Carnot battery. The results show that with gas price of 9.3 EUR/GJ incl. Transport the energy system cost reductions are in the range of 60.5–66.2 EUR/$MWh_{e,dis}$. 95% of the setups show cost reductions are between 62.6 and 66 EUR/$MWh_{e,dis}$. The main difference in cost reductions is related to what type of gas turbine, simple-cycle or combined-cycle, that the Carnot batteries mainly replace when discharging. Replacement of production from simple-cycle gas turbines provides larger cost reductions for the system than replacement of

Table 1
Sensitivity of energy system cost reductions per $MWh_{e,dis}$ from the Carnot batteries at different levels of RTE, discharge capacity in pct. Of charge capacity, charge capacity and storage capacity in days of charge capacity. Investment and O&M costs for Carnot batteries are not included.

			Replace electrolysis			Replace electrolysis and incr. Wind power		
			Days of storage			Days of storage		
RTE	Discharge	Charge	1	4	7	1	4	7
15%	12,5%	500	43	41	41	−68	−45	−92
		2000	40	40	40	−58	−85	−78
	50%	500	43	40	40	−80	−79	−63
		2000	40	39	38	−75	−83	−88
	100%	500	43	40	40	−80	−79	−63
		2000	40	38	38	−75	−85	−89
45%	12,5%	500	42	41	41	5	36	36
		2000	40	40	40	11	16	16
	50%	500	41	40	40	21	19	17
		2000	39	38	38	16	14	11
	100%	500	41	39	39	19	12	13
		2000	38	38	38	14	11	12
75%	12,5%	500	41	41	41	24	43	43
		2000	39	40	40	29	36	36
	50%	500	40	40	40	46	36	36
		2000	38	38	38	34	31	33
	100%	500	40	39	39	39	34	30
		2000	38	38	38	27	32	32

combined-cycle gas turbine, as simple-cycle gas turbines have an electric efficiency of 45%, whereas combined-cycle plants have one of 63% in the IDA2045 scenario (based on lower-heating value). As such, those with large cost reductions tend to replace more simple-cycle gas turbine production than those with relatively low-cost reductions, due to differences in reduction of gas consumption for the power plants. Which gas turbine technology the different Carnot battery variations replace dependents on the variations charge and discharge cycle. EnergyPLAN simulates the year chronologically with limited forecast of the rest of the year when deciding to charge and discharge the Carnot batteries. Therefore some lower RTE setups can show slightly better cost reduction per $MWh_{e,dis}$ as they, by coincidence, can end up replacing more simple-cycle turbines than setups with higher RTE. Using other distributions for variable RES production and energy demands could affect this, and it is thereby important to focus on the general trends shown in the figure.

3.3. Sensitivity analysis

In the simulations it is assumed that no changes are made to the investments in the remaining energy system when introducing Carnot batteries. In this sensitivity analyses two methods for identifying the potential cost reduction of Carnot batteries by reducing investments in other flexible technologies.

In IDAs Climate Response 2045 the electrolysis capacity is set to 4.8 GW. However, with an average operation at 3 GW the electrolysis capacity is deliberately over dimensioned as to allow for flexible operation using the hydrogen storage of 320 GWh, which in turn allows for more utilization of variable RES. Introducing Carnot batteries could allow for less need for this over dimension of electrolysis and hydrogen storage capacities. As such, in the first new method, the electrolysis and hydrogen storage capacities are adjusted based on the operation of the Carnot battery variations. The capacities of these technologies are adjusted so that the yearly net gas exchange is the same as without the Carnot batteries. For simplicity it is assumed that the relative relationship between the capacity of the electrolysis and hydrogen storage remains unchanged, so that when the electrolysis capacity is decreased the hydrogen storage capacity is decreased by the same percentage. In IDAs Climate Response 2045 the investment cost of the electrolysis is 0.6 M EUR/MW_e with a lifetime of 20 years and a yearly fixed O&M of 3% of the investment cost. The hydrogen storage has an investment cost of 29.7 M EUR/GWh with a lifetime of 48 years and a yearly fixed O&M of 0.01% of the investment cost.

In the second new method the same adjustments are done to electrolysis and hydrogen storage capacities as in the first method, though in the second method offshore wind power is added to the system up to a level where the yearly CEEP value remains unchanged. Adding more offshore wind power might allow the Carnot batteries to have more cycles as there will be more CEEP in the energy system, however, adding more offshore wind power will also affect the operation of other units in the energy system, such as CHP and heat pumps, and these affects are also taken into the account in the simulations in EnergyPLAN. In IDAs Climate Response 2045 offshore wind power has an investment cost of 1.9 M EUR/MW_e, a lifetime of 30 years and a yearly fixed O&M of 2.51% of the investment cost.

The sensitivity analyses are only carried out using 54 variations of the Carnot batteries, making up the most extreme variations and some in-between variations. The results of the sensitivity analyses, including adjusted capacities, are shown in the supplementary material. The cost reduction per average $MWh_{e,dis}$ to the grid for the sensitivity analyses are shown in Table 1.

As shown in Table 1, reducing the capacities of electrolysis and hydrogen storage result in a cost reduction in the range of 38–43 EUR/$MWh_{e,dis}$ with smaller Carnot battery variants showing larger cost reductions with 15% RTE and at 75% RTE the cost reduction per $MWh_{e,dis}$ is similar for all variants.

In the second method, where offshore wind power is added, the largest cost reduction per $MWh_{e,dis}$ being 46 EUR/$MWh_{e,dis}$ at 75% RTE, 0.5 GW_e charge, 0.5 GW_e discharge and 1 day of storage. Larger storage capacities generally show a lower cost reduction per $MWh_{e,dis}$ due to diminishing energy system benefits. It is also clear that when using this method, the RTE becomes very important for the cost reductions, with 15% RTE only showing worse economic results as significantly more offshore wind power must be added to keep the same yearly CEEP to make up for the loss in the Carnot batteries.

Generally, both these methods show lower cost reduction potentials per $MWh_{e,dis}$ than with the method used in section 3.2.

4. Discussion

In this section, the economic potential of Carnot batteries identified by the 1120 simulations presented in section 3 is put into perspective by presenting today's cost of different Carnot battery types. As introduced in section 1.1, these types differ in both technical as well as economic aspects.

Above-presented results indicate that Carnot batteries need to achieve costs at or below 60.5–66.2 EUR/$MWh_{e,dis}$ for cost neutrality in a 2045 scenario with 100% renewables. As also described in section 2.3, since this value should include the total expenditure over the full lifetime of a Carnot battery, it corresponds to the increasingly used LCOS. However, this range is heavily dependent on the gas price, as the main cost reduction is found by a reduced usage of gas-fired power plants. In the paper, a gas price for power plants of 9.3 EUR/GJ incl. Transport costs is used as it corresponds to price projections for biogas. However, as also mentioned in section 2.3, gas prices could be even higher as gas is traded internationally and the international market price could be set by more expensive ways of producing gas, with electro-methane showing the highest cost that could be around 18.1 EUR/GJ [40]. If the gas price would reach electro-methane levels the LCOS range would instead be around 119–130 EUR/$MWh_{e,dis}$.

It should be noted this paper takes into account the production cost of electricity since a dominating share of literature (e.g. Ref. [42]) does so, while some authors (e.g. Ref. [43]) exclude the electricity costs for their specific comparison purposes and these are therefore excluded from the comparison within this work. Also, for the calculation of capital expenditures, different approaches exist. The two most relevant approaches are the use of power- or capacity-specific costs. But since both

Table 2
Comparison of main LCOS driver related to the Carnot battery itself; based on a recent literature review [21]. Reported for mostly full-scale, commercial or even future systems.

	Rankine CB	Brayton CB	LAES
Power-specific costs in EUR/kW$_{out}$ (mean)	476–7619 (2857)	1904–3810 (3238)	667–2857 (1333)
Capacity-specific costs in EUR/kWh$_{stored}$ (mean)	238–952 (286)	48–1429 (595)	380–762 (333)
RTE in % (mean)[a]	45–65 (55)	52–70 (61)	40–60 (50)

[a] Converted to EUR by using the €-$ exchange rate from 2022, as given in Table A1.

installed power and storage capacity determine the capital expenditures, in reality, a component-level analysis with individually selected specific costs promises highest accuracy. By doing so, it is considered that e.g., turbomachinery costs usually scale with power while the thermal storage cost predominantly depend on the total capacity and hence material used. Together with the RTE, the power- and capacity specific costs are the main LCOS driver stemming from the Carnot battery itself. Table 2 lists these for different Carnot battery types.

Even though the large interval for the three LCOS driver listed is striking, all three Carnot battery types are characterized by relatively low mean capacity-specific costs compared to those of e.g. Li-Ion batteries (up to 857 EUR/kWh$_{stored}$ [44]), making them particularly relevant for long storage durations. In addition to that, specific costs of batteries typically do not decrease as significantly as they do for Carnot batteries during scale-up [45]. However, the choice of Carnot battery type is highly dependent on the specific scenario and associated boundary conditions: In a scenario with high electricity prices for example, Brayton PTES with a higher RTE could be characterized by lower LCOS even though LAES have lower capital costs.

Fig. 7 presents literature values for the LCOS of 14 different Carnot battery systems as well as 8 systems based on established storage technologies, namely Li-Ion batteries and pumped hydro storages, relativized under consideration of historical exchange and inflation rates. Here, the only Carnot battery system below the identified 62 EUR/MWh$_{e,dis}$ threshold is a Brayton Carnot battery with a particle thermal energy storage integrated with an efficient air-Brayton combined cycle power system [46]. This system is still in conceptual phase, and we assume that it notably benefits from its target of 13.5 GWh storage capacity, the largest storage capacity of all presented systems. In that context, it should be noted that the storage capacities of all other Carnot battery systems are ≤1 GWh. This differs from the variations applied in the 1120 simulations of this work, but as the energy system analysis is a countrywide analysis, it also covers the potential for installation of several Carnot batteries, and future developments of Carnot batteries could also lead to larger capacities for each facility. However, lowest costs do not necessarily occur for the largest system, as stated by Ref. [47] for LAES, even though there is a clear trend of rising LCOS for smaller capacities of Brayton CB in Fig. 6 observable. Overall, the current LCOS of Carnot batteries spread wider than those of established storage technologies but can be considered competitive today; McTigue et al. already expect competitiveness from storage durations above 6 h [48]. This competitiveness is additionally supported by the projection that pumped hydro as well as Li-Ion batteries will see a decreasing cost reduction over the next decades [49]. When comparing the results from our study, with the alternative cases presented in Fig. 7, it is important to note that difference in charge cycles is not considered. Hence, the proposed Carnot battery technologies not only has to be able to achieve LCOS lower than 76 EUR/MWh, but they also need to achieve it with less than 32 yearly charge cycles.

To finalize the discussion of results, the authors would like to highlight the limitations of LCOS evaluations in general. Within the comparison done in this work, no quantitative consideration of different services and their corresponding operation scheme takes place. Furthermore, no particular attention is given to the location of each system, potentially having a relevant impact on labor costs, electricity price or discount rate. Also, private economic operation strategies will depend on several factors. In the study this is not considered. Thus, the paper does not take into difference between subsidized and unsubsidized systems, with or without degradation or project insurance consideration. Business economic operation will concern the electricity price since Carnot batteries are inherently characterized by a proportion of charging costs over the total expenditures due to low capital expenditures and RTE. Also, in this work the electricity price is only based on the cost of producing electricity, and as such, do not include other aspects that could affect the electricity price, such as profit margins, market structure, taxes and tariffs.

5. Conclusion

In this paper the economic effects of including Carnot batteries in a 100% renewable energy system is analyzed to estimate a target LCOS for the development of Carnot batteries. The results show that Carnot batteries can be used to reduce the use of power plants, and thereby reduce the use of renewable fuels for these. The Carnot batteries are found to have between 3 and 32 yearly charge cycles depending on the capacities

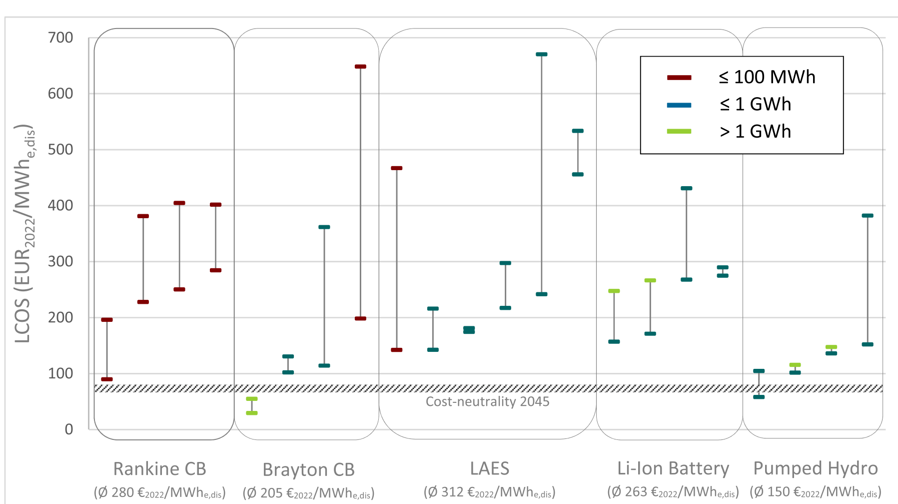

Fig. 7. LCOS of different Carnot battery types as well as established storage technologies including the corresponding storage capacity ranges. For comparability, historical exchange as well as inflation rates are considered as listed in Appendix A1. References for the systems from left to right: [42,42,45,45,45,45–55,55–60].

of the storage with smaller storages having more yearly charge cycles than larger. The main cost reduction of Carnot batteries in the system is the reduction in fuel used in the power plants. In the used scenario the power plants are gas-fired utilizing upgraded biogas. Thereby the expected economic gains of the Carnot batteries are, in this scenario, found to be directly connected to the international price of gas. The gas price used in the scenario is 9.3 EUR/GJ incl. Transport costs corresponding to price projections for biogas, which shows LCOSs of Carnot batteries in the range of 60.5–66.2 EUR/$MWh_{e,dis}$. If the potential cost reduction is instead identified based on reducing capacities for electrolysis and hydrogen storage the LCOSs drops to 38–43 EUR/$MWh_{e,dis}$, depending on the cost of these components. From the literature only one Carnot battery system concept has been identified with a LCOS lower than the 62 EUR/$MWh_{e,dis}$ threshold, being a system still in the conceptual phase. Therefore, solutions for cost reductions should be investigated further for the Carnot battery technology to be relevant in large-scale for electricity storage purposes.

CRediT authorship contribution statement

Peter Sorknæs: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing, Funding acquisition. **Jakob Zinck Thellufsen:** Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing, Funding acquisition. **Kai Knobloch:** Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Kurt Engelbrecht:** Conceptualization, Writing – review & editing, Funding acquisition. **Meng Yuan:** Writing – review & editing.

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.

Acknowledgements

The work presented in this paper was funded by the Danish national EUDP grant - J. nr. 64019–0520 - to support the Danish participation in the international IEA project “IEA Energy Storage Task 36 – Carnot Batteries”.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2023.128837.

Appendix

Table A1
Exchange as well as inflation rates used for this work.

Year	Exchange rate €-$ (–)	Exchange rate £-€ (–)	Inflation rate € (%)
2022	1.05	0.85	9.90
2021	1.18	0.86	2.66
2020	1.14	0.89	0.74
2019	1.12	0.88	1.47
2018	1.18	0.88	1.89
2017	1.13	088	1.71
2016	1.11	0.82	0.25

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