How can energy-system models inform technology development? Insights for emerging energy-storage technologies

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ABSTRACT

Energy-system models (ESMs) are often used to support policymakers, system operators or investors, but fall short of offering guidance to technology developers. This paper aims to bridge the gap between energy-systems modelling and technology development. Focussing specifically on electricity-storage technologies, we highlight how ESM outcomes can inform the development of emerging technologies. We use a model that includes four promising energy-storage technologies in a capacity-expansion and dispatch optimisation of the European electricity system with a constraint that allows zero carbon emissions before the year 2050. Our model outcomes are geared towards informing technology developers, particularly regarding optimal energy-to-power ratios, full-cycle equivalents, dispatch curves, and promising markets. We link these design and dispatch decisions with each other and with energy-storage characteristics (*e.g.*, capital expenditures and efficiencies) and with renewable-energy potentials of different countries. The insights that are generated can support developers, *e.g.*, by providing guidance on operational requirements or trade-offs in design decisions. We conclude that there are no significant barriers to informing technology development with ESMs. However, future work should improve the representation of technological details and develop inverse modelling approaches for technologies in very early development stages with still highly uncertain parameters.

1. Introduction and motivation

Energy systems around the world are transitioning towards sustainable energy to reduce emissions and limit the effects of climate change (Chen et al., 2019; Kabeyi and Olanrewaju, 2022). In this context, both governments and private actors worldwide invest enormous resources into developing clean-energy technologies to provide and improve the necessary technologies to realise a functioning, climate-neutral, global energy system (IEA, 2024). Therefore, governments need to be informed about the benefits of spending public resources, companies need information to manage their technology-development portfolios, and there may also arise the need for universities or research institutions to (re)direct their research programmes to maximise societal benefits (Faúndez, 2008; Wang, 2020).

Successful energy-technology developments lead to adoption decisions by energy-market participants, resulting in benefits for the energy system and its sustainable transition as well as profit for the technology adopters. Hence, it is worthwhile to shed light on decision making by different market actors in the energy sector, particularly concerning decisions on the development and use of energy technologies under uncertainty (UNEP Collaboration Centre of Energy and Environment, 2002; Sen and Ganguly, 2017). Tension is growing between leveraging economic growth through research and development and ever-increasing costs of the energy transition putting pressure on energy budgets (Altıntaş and Kassouri, 2020; Caglar and Ulug, 2022). Therefore, it will become increasingly important to

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assess the economic and system benefits of energy technologies during earlier stages of technology development and implementation (Blazquez et al., 2020; Moriarty and Honnery, 2022; Kamali Saraji and Streimikiene, 2024).

The analysis of energy technologies can help to improve the quality of government decisions in the energy field (Gilliland, 1975). Consequently, energy system models (ESMs) have been developed and used for decades (Hoffman and Wood, 1976). ESMs can be classified as either top-down or bottom-up models. Top-down models pursue a macro-economic approach, which considers the whole economy (of the analysed region), but neglect some technical characteristics of the energy systems. Conversely, bottom-up models focus solely on the energy sector (many only on the electricity sector), but aim to realise a rather detailed representation of existing and future energy technologies (Böhringer and Rutherford, 2008; Bublitz, 2019; Sensfuß, 2007).

Over the more than 50 years of experience with ESMs, modellers have learned about opportunities and limitations of these models. The objective of using ESMs cannot be to predict accurately future energy systems, *e.g.*, the development of electricity prices or the technology mix over the next 20+ years. The experience with ESMs made clear that we should model for insights rather than for specific trajectories (Huntington et al., 1982). There are several reasons why we should restrict the use of ESMs to this objective, starting with the trivial statement that even extremely sophisticated models are simplifications of reality. However, most important is the insight that the future (energy system) is not fixed, but will be influenced by the decisions that are taken today. This leads to the main objective of ESMs: putting today's decisions on a more rational basis by identifying robust decisions (Voß, 1982).

With regard to the target audience, ESMs are applied primarily to provide decision support to policymakers, and much less to inform energy-technology developers. This is surprising, because technology developers would benefit from guidance that can be provided by ESMs, *e.g.*, on the probability of a sufficient return on investment or requirements for novel technologies from the perspective of the system or market (Klein and Meckling, 1958; Veldhuizen et al., 2006). We posit that the lack of collaboration between the ESM discipline and technology developers may be at least in part due to a gap in technology readiness levels (TRLs) on the spectrum between established technologies that are operational and emerging technologies that are undergoing development, demonstration, and testing. Bottom-up optimisation or simulation models, which are able to represent technological details of energy technologies, seem to be the tool of choice for informing technology developers. These models work best for technologies with high TRLs (*e.g.*, TRL 7 and above), because meaningful estimates of the costs and efficiencies of such technologies, which are key input parameters for ESMs, are available within reasonably small ranges. This reality explains also why ESMs are used frequently to support decision making of investors (*e.g.*, utilities) in the energy sector, which invest usually in relatively high-TRL technologies. However, for emerging technologies, *e.g.*, with TRL 5 and below, estimations of cost or efficiency are often impossible or carry enormous uncertainty.[1] Therefore, the following three questions arise, which guide the research that is presented in this paper. First, are there any profound barriers to informing technology development with ESMs? Second, how can energy technology development benefit from the information that is provided by ESMs? Finally, what methodological developments are needed to enable ESMs to provide this form of decision support and guidance?

In this paper, we focus on energy-storage technologies, which is particularly relevant because the availability of affordable, location-independent, resource-conserving, and scalable energy storage remains an unsolved challenge in transitioning to carbon-free energy systems (Loisel, 2012; Gür, 2018; Sepulveda et al., 2021). There are a number of studies, including our own, that analyse energy-storage requirements for energy systems. However, these studies are aimed mostly at providing high-level decision support to policymakers by analysing feasible and economically efficient technology mixes for future energy systems that meet predefined policy goals (Moser et al., 2020; Sioshansi et al., 2022; Levin et al., 2023; Mutke et al., 2023). This does not mean necessarily that the ESMs that are used are not suited to support technology development. However, minimally, this means that the results that are reported are not geared towards the needs of technology developers. Absent appropriate input from the ESM discipline, technology developers frequently need to make rather crude assumptions on the potential behaviour of "their" technology in the market (Smallbone et al., 2017; Georgiou et al., 2018; Bashiri Mousavi et al., 2021). Thus, to narrow the gap between the ESM discipline and technology developers, we demonstrate in this paper how results from ESMs can be used to inform the development of emerging energy-storage technologies.

The remainder of this paper is structured as follows. Section 2 provides a brief summary of the state of the art of techno-economic analysis, in particular using ESMs, of energy-storage technologies and energy systems and explains the research gap. Section 3 describes the model and data used to illustrate the potential role of ESMs in informing

[1] We acknowledge that uncertainties concerning future technology costs are high also for established technologies. The uncertainty is significantly higher for emerging technologies, however.

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technology development. Section 4 provides a selection of results from an ESM that is geared towards supporting technology developers. Section 5 provides insights to both technology developers and energy-system modellers as well as the main limitations. Section 6 concludes this paper and provides an outlook on future research requirements.

2. State of the art and research gap

The existing literature on techno-economic analyses of energy-storage technologies and their behaviour in energy systems largely falls into the following three broad categories.

First are studies that focus on a comparison of the *cost side* of different technologies, while the technologies' market values and market-based revenue opportunities are typically not assessed in detail. These studies are conducted mostly by the technology-development disciplines. Hence, such studies typically are technologically detailed. In these studies, the economic evaluation of technologies typically involves calculating metrics such as the specific investment cost or the levelised cost of storage (LCOS).

For example, Georgiou et al. (2018) consider pumped-thermal energy storage (PTES)[2], which they assume to operate 365 cycles per year (one cycle per day). Going beyond such studies, of interest to us here is to explore whether there is a need for or whole-system benefit of such a technology operating at this frequency. Smallbone et al. (2017) calculate the LCOS of a PTES system and find that these are in a similar range as those of compressed air energy storage and vanadium-redox flow batteries, when assuming 365 cycles per year. They consider a fixed "energy-to-power" (E2P) ratio[3] of 8 hours and an exogenously fixed ratio of 1.25 between the charging and discharging power capacities. In their sensitivity analysis, Smallbone et al. (2017) emphasise that the LCOS are sensitive to assumptions on the operating profile as well as the assumed costs and efficiency. Likewise, McTigue et al. (2022) explore recuperated PTES systems and estimate how the LCOS changes with varying charging and discharging durations. Their analysis shows that the minimum LCOS is achieved when the ratio between the charging and discharging durations is approximately 1.4. Recent technical investigations, including the works of Dumont and Lemort (2020); Frate et al. (2020); Dai et al. (2023), combine energy storage with thermal waste energy recovery, often utilising heat sources at temperatures between 50°C and 90°C. Such configurations, however, combine aspects of energy-storage systems and energy upgrading/conversion devices. In their LCOS calculation, (Dai et al., 2023) assume 365 cycles per year with a charging duration of 10 hours and a discharging duration of 6 hours.

Mersch et al. (2023) consider adiabatic compressed air energy storage (ACAES), which – similar to PTES mentioned above – is a type of thermo-mechanical energy storage technology (Olympios et al., 2021). The authors focus on evaluating different technical configurations without modelling the energy system in which the ACAES is integrated. Instead, the energy storage is optimised for maximum roundtrip efficiency and minimum specific capital costs, assuming fixed charging and discharging durations of 3, 6, and 9 hours and power ratings of 10 MW, 50 MW, and 100 MW. Similarly, Barbour et al. (2015) investigate a 500-kW, 2-MWh ACAES system, which is assumed to be charged over night and discharged during the daily evening peak demand. The energy storage is charged every day between 2:00 AM and 6:00 AM, remains fully charged during the following 10 hours, and then is discharged between 4:00 PM and 8:00 PM, before sitting idle between 8:00 PM and 2:00 AM. Sciacovelli et al. (2017) investigate the transient operation of an ACAES system assuming similar daily cycles as Barbour et al. (2015). The system is assumed to be charged between 3:00 AM and 1:00 PM and discharged between 6:00 PM and 10:00 PM. Bashiri Mousavi et al. (2021) also model the transient operation of an ACAES system. They assume that the energy storage is charged for six hours before immediately being discharged for four hours. In our study, we go beyond these assumptions by proposing to consider information from ESMs in the design and evaluation of different energy storage systems.

This category of technical studies is valuable for the design and comparison of different technologies, but faces certain limitations. Firstly, different revenue streams are not considered in the calculation of the LCOS. Given that private investors value profitability, which may be substantial despite high costs, an analysis of potential revenues is important when making investment decisions. Finke et al. (2023) make a similar argument in the context of renewable-energy investments. Secondly, the assumptions regarding the store's operation profile can significantly influence the economic results. Information from ESMs can be valuable to ensure that these assumptions are well aligned with the energy system needs. Thirdly, static assumptions on operation profiles and electricity tariffs cannot capture the potential feedback of technology characteristics on the entire energy system. (Cebulla et al., 2017) show and this paper confirms

[2]PTES also is referred to as a Carnot battery, pumped heat energy storage or, less specifically, power-to-heat-to-power energy storage.

[3]The E2P ratio is defined as the quotient of the energy-storage capacity (measured in MWh) and the discharge power (measured in MW) of energy storage. Hence, E2P is measured in hours.

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that the number of full cycle equivalents (FCEs) per year,[4] that is economically viable for the energy-storage owner and beneficial to the energy system in which it operates depends on the E2P ratio of the energy storage. The optimal choice of E2P ratio depends on the costs of energy-storage capacity and charging and discharging power of the technology as well as characteristics of the underlying energy system (*e.g.*, shares of renewable and flexible generation and other energy storage). The underlying energy system may be driven by the costs and efficiencies of available energy-storage technologies. Static assumptions on the energy-storage operation are unable to reflect such feedbacks (Finke et al., 2023).

The second category of studies involves analysing energy-storage technologies using a profit-maximising approach relying upon exogenous (typically historical) electricity prices as an input. Such studies are conducted both by technology developers and energy-market analysts, as the profit maximisation reflects (at least to some extent) the perspective of investors.

For instance, Frate et al. (2021) compare different energy-storage technologies based on data from the Italian market. The authors consider E2P ratios between 4 and 10 hours and varying round-trip efficiencies. Their results suggest that the investigated technologies are not economically viable as of the time of the study. However, potential technology improvements or energy-market changes could enhance their economic feasibility. Similarly, Spodniak et al. (2021) investigate key factors that influence the economic viability of large-scale, centralised energy storage in day-ahead electricity markets of Germany, the United Kingdom, and Scandinavia. The study considers E2P ratios between 1 and 13 hours. The study shows that German solar electricity increases the energy-storage utilisation. However, it has a negative impact on the economic viability of energy storage due to decreased electricity-price spreads caused by daytime solar generation. Braeuer et al. (2019) assess the profitability of battery energy storage for German small- and medium-sized enterprises. They find significant potential profits when considering revenue streams from the provision of primary control reserve compared to a case wherein batteries arbitrage spot-market energy-price differences only. Laterre et al. (2025) conduct a techno-economic analysis of Carnot batteries for energy management in residential settings. They find that in cases where heat pumps and thermal energy storages are needed to supply residential heating demand, adding a heat engine to provide electricity can be financially attractive. Chen et al. (2024) analyse the economic viability of underground hydrogen-storage systems for long-duration grid-scale electricity storage and find that profitability can be achieved for an appropriate mix of revenue streams.

While these approaches can indicate potentially attractive markets and applications of energy storage systems, the profitability is assessed on the basis of historical electricity-price time series of the corresponding markets. Thus, such studies are unable to capture the future development of electricity prices, including potential feedbacks between the market and energy storage deployment. In contrast, Sioshansi et al. (2009) study the value of electricity storage in an eastern United States of America (US) market and explicitly compare the arbitrage value with and without considering the feedback effect of energy storage arbitrage on electricity-market prices. However, this analysis is based on an ordinary-least-squares estimate of an assumed linear price-demand relationship using historic prices of one month. Dynamic changes in the underlying electricity system are not considered. In our analysis, we go beyond that by capturing effects of energy storage on the economic attractiveness of other technologies (*e.g.*, renewable energy) in the electricity system, which may have feedback effects on the economics of energy storage. Furthermore, we are able to capture future large-scale changes in electricity systems (*e.g.*, the decommissioning of fossil-fueled generators or the expansion renewable energy) which are not reflected in historical electricity price profiles.

The final category are studies aimed at analysing energy-storage needs from an energy-system perspective. Such studies use ESMs to consider dynamic energy-system interactions.

Weitemeyer et al. (2015) examine the energy-system's demand for energy storage as a function of the share of renewable energy generation. Considering different existing energy-storage technologies with varying efficiencies, costs, and capacities, they show that inter-seasonal energy storage is only a part of the least-cost energy-system design for electricity systems with more than 80% of electricity being supplied by renewable energy. Babrowski et al. (2016) investigate the spatio-temporal development of energy-storage demand in Germany and identify the future energy-storage demand, especially in the vicinity of offshore wind generators. Solomon et al. (2017) investigate the need for energy-storage technologies in future electricity supply systems in California and Israel with renewable energy supplying 90% of electricity. Arbabzadeh et al. (2019) focus on the impact of energy storage on the curtailment of renewable-energy generation and show that in California, energy storage can increase carbon-emissions reductions due to expanding the supply of renewable energy by 20%. Moser et al. (2020) present comprehensive sensitivity

[4] FCEs per year is calculated as the total energy discharged over one year (in MWh) divided by the invested energy-storage capacity (in MWh), and is dimensionless.

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analyses on the impact of energy-storage costs and capacities on energy-storage demand in different regions of the European electricity system. They find that hydrogen storage is mostly deployed in regions with high wind-electricity shares, while batteries are more distributed throughout Europe. Mutke et al. (2023) analyse installed capacities of different energy-storage technologies in a European electricity system across different decarbonisation levels. They report the results at an aggregated European level and assess the impact of bioenergy and transmission-line expansion on energy-storage requirements. Heredia-Fonseca et al. (2024) use an ESM to identify and analyse 100% renewable energy pathways for the Indian state of Goa. Their study is focussed on energy technology mixes along the pathway rather than operational details.

All of these system-level approaches allow us to study least-cost future electricity systems including the interactions between existing and emerging technologies in the system under different constraints. However, while providing useful information, they do not focus explicitly on the needs of technology developers, who may seek to gain insights into a different set of questions. For instance, a technology developer may seek to understand trade-offs between technology performance (efficiency) and costs, which could help to prioritise development (*i.e.*, a low-cost/low-performance as opposed to a high-cost/high-performance technology). This possibility was explored by Olympios et al. (2024) in the context of heat-pump systems, for example. In the specific context of energy storage technologies, other design details that may be of interest to technology developers include required E2P ratios (*i.e.*, the need for short- or long-duration energy storage) and the number of FCEs per year. Operational and economics details that are outputs of ESMs may help inform technology choices. For example, dispatch curves can inform needed ramping capabilities, while future electricity-price profiles and spreads can inform economic viability, and disaggregated investment requirements and prospective market volumes can inform which markets are most promising for a given technology.

In summary, while most studies of the first two groups are technologically detailed, they are not designed to capture dynamic interactions with electricity markets, which will change fundamentally during the coming decades. These changes stem mainly from the evolving technology mix of underlying electricity systems (as they transition towards sustainable energy), which will change the (marginal) cost structures of electricity supply. In constrast, models used in the third group of studies are designed explicitly to capture such dynamics. However, these studies are typically intended to support policymakers or investors, but are often not aimed at providing results that offer guidance to technology developers. An exception, beyond the aforementioned study by Olympios et al. (2024) on domestic heating systems, is the paper by Sepulveda et al. (2021), which analyses the so-called design space of long-duration energy storage. By varying a selection of design parameters of such technologies, they focus on technology costs and efficiencies. Through a multi-parameter analysis, they identify minimum efficiencies and maximum costs that long-duration energy-storage technologies would need to meet to be deployed and provide value to the energy system. Their analysis considers two US electricity systems and analyses several sensitivities. In this paper, we go beyond this analysis by considering more energy systems and explicitly investigating the impact of the underlying electricity systems' technology mixes (*e.g.* solar- or wind-dominated). Moreover, we provide information on expected dispatch curves or expected market volumes. Another exception is the study by Cebulla et al. (2017), which analyses the capacity requirements, spatial distribution, and dispatch of electrical energy storage in a European electricity system with high penetrations of renewable energy. Their findings show how the spatial distribution of different energy-storage technologies (long- as opposed to short-term) are influenced implicitly by renewable energy sources. In their paper, they use a constraint that enforces a minimum of 80% of electricity supply from variable renewables and report that the share resulting from their model yields exactly this minimum requirement of 80%. Since they formulate the constraint as a minimum share of renewables as opposed to a maximum amount of CO_2 emissions, the resulting energy system in 2050 still includes fossil generators. In our paper, we go beyond this approach by formulating a constraint on emissions, which allows for including emission-free systems in our analysis.

In summary, this paper contributes to closing further the gap between ESM and technology development. The paper provides illustrative examples of results that can be taken from an ESM and which are useful for technology developers. However, the paper's main focus lies on the process of discerning such results and the benefits that can be gained from a closer collaboration between the ESM and technology-development disciplines.

3. Methods and data

This paper builds on a European electricity-system model for the year 2050, which was developed by Mutke et al. (2023). The model was previously used to inform policymakers with highly aggregated results. This paper informs

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energy-storage-technology developers, by analysing and interpreting previously unconsidered, disaggregated results, particularly nationally and temporally resolved data.

The linear optimisation model represents the power systems of 21 European countries during the 2050 target year at hourly resolution under varying CO_2-reduction targets. The model is built using the open-source energy system optimisation framework, Backbone (Helistö et al., 2019), which structures networks using nodes, grids, units, and lines. In the underlying model, most countries are represented by one node, whereas Germany is modelled with 10 nodes, as is depicted in Figure 1. Using a brownfield planning approach, the model minimises total system costs under perfect foresight.



Figure 1: Geographical region under study; black lines represent borders between nodes.

Besides standard constraints that are related to energy balance and conversion, which are detailed by Mutke et al. (2023); Helistö et al. (2019), each unit's output is restricted by its capacity. In addition, the amount of added capacity can be restricted. Specifically for each energy storage, s, energy balance is enforced during each time step, t, by:

$$v^{\mathrm{SoC}}_{s,t} = (1-\sigma_s)v^{\mathrm{SoC}}_{s,t-1} + \eta^{+}_{s} v^{+}_{s,t} - \eta^{-}_{s} v^{-}_{s,t}. \tag{1}$$

The state of charge, $v^{\mathrm{SoC}}_{s,t}$, can change due to charging, $v^{+}_{s,t}$, discharging, $v^{-}_{s,t}$ (which account for efficiencies, η^{+}_{s} and η^{-}_{s}), and self-discharge losses, σ_s. The three decision variables that represent the state of charge, charging, and discharging during each time step are limited by capacity variables:

$$v^{\mathrm{SoC}}_{s,t} \leq v^{\mathrm{max\,SoC}}_{s} \tag{2}$$

$$v^{+}_{s,t} \leq v^{\mathrm{max}+}_{s} \tag{3}$$

$$v^{-}_{s,t} \leq v^{\mathrm{max}-}_{s}. \tag{4}$$

Moreover, CO_2 emissions have an upper limit of zero, *i.e.*, we focus on the "$C100$" scenario of Mutke et al. (2023), which yields a fully decarbonised European electricity system. While natural-gas and nuclear generators are assumed to be already installed (coal and oil generators are decommissioned), based on historical capacities, the investment into renewable generation and energy-storage technologies is endogenously optimised to achieve decarbonisation at least cost. The generation technologies that are available for endogenous investments are onshore and offshore wind, solar photovoltaic, and bioenergy. Moreover, four potentially promising large-scale energy-storage technologies can be built: lithium-ion batteries (LIB), vanadium redox-flow batteries (VRFB), ACAES, and hydrogen storage (H_2). For all energy-storage technologies, the size of the energy reservoirs and power rating can be determined independently, *i.e.*, the E2P ratios are endogenous decisions. For H_2, the charging and discharging capacities can also be determined independently, while for LIB, VRFB, and ACAES, there is no distinction between the two, *i.e.*, their ratios are fixed to

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Table 1
Techno-economic input data of the four energy-storage technologies that are available for investment. $CAPEX_{power}$ indicates the investment costs of 1 kW combined charging and discharging power (except for hydrogen storage, where both capacities can be determined independently). $CAPEX_{energy}$ indicates the investment costs of 1 kWh of energy-storage capacity, which can be sized independently of the power capacity. The quotient of the two is called E2P CAPEX ratio, where for hydrogen storage we have added 1 kW charging and 1 kW discharging capacity in the denominator. Using the lifetime and a discount rate of 7%, the annualised CAPEX (in €/kW(h)/a) is calculated. Note that the E2P CAPEX ratio does not change with annualising the CAPEX, except for hydrogen storage. All data are taken from Mutke et al. (2023).

Energy-storage technology	$CAPEX_{power}$ (€/kW)	$CAPEX_{energy}$ (€/kWh)	E2P CAPEX ratio (1/h)	Overall efficiency (%)	Lifetime (a)	Annualised $CAPEX_{power}$ (€/kW/a)	Annualised $CAPEX_{energy}$ (€/kWh/a)
Lithium-ion battery (LIB)	74	155	2.095	93	17	7.58	15.87
Vanadium redox-flow battery (VRFB)	333	96	0.288	81	23	29.54	8.52
Adiabatic compressed air energy storage (ACAES)	823	48	0.058	70	45	60.49	3.53
Hydrogen storage[a] (H_2)	267 // 767	0.5	0.0005	78 // 60	13 // 28	31.96 // 63.20	0.06

[a] Hydrogen generation with PEM // re-electrification with gas turbine.

unity. Moreover, cyclic boundary conditions are enforced for all energy-storage technologies, *i.e.*, their initial states of charge are determined endogenously but must match their ending states of charge.

The open-source model PyPSA-Eur (Hörsch et al., 2018) is the main data source for transmission capacities, existing conventional generators, demand and weather time series (which correspond to year-2013 data), and nodal clustering. Techno-economic data, most importantly costs, capital expenditures (CAPEX), technical lifetimes, and efficiencies, are synthesised from various sources by Mutke et al. (2023), as summarised in Table 1 for the expandable energy-storage technologies. Further details of the underlying model are provided by Mutke et al. (2023).

The main model outputs, *i.e.*, the primary decision variables, are: (i) the invested capacity of (renewable) generators at each node; (ii) the invested energy-storage power and energy-storage capacities (thus, also, the E2P ratios) at each node; and (iii) hourly operational time series of generators and energy storages, in particular the state of charge. Based on these outcomes, the residual load can be calculated by subtracting the generation of all variable renewable generators (wind, photovoltaic solar, and run-of-river hydroelectric) from the hourly electricity demand. Moreover, the FCEs of energy storages can be calculated as the total energy discharged over one year divided by the invested energy-storage capacity.

4. Results

To establish a baseline and provide fundamental results for the fully decarbonised electricity system that is modelled, Mutke et al. (2023) discuss the aggregated electricity mix and energy-storage capacities. They observe the following trends. With decreasing emissions, natural-gas generation is replaced by renewable electricity supply, while overall electricity generation increases due to increased energy losses that are associated with energy-storage use. Energy-storage capacities increase with decreasing emissions, with LIB being built first and, for all decarbonisation targets except 100%, having the greatest capacity. H_2 capacities increase drastically from 0 GW in the cost-optimal case without an emission target to up to around 300 GW at 100% CO_2-emission reduction. VRFB and ACAES are built only for CO_2-emission reductions above 80%, with capacities always below 15 GW. Figure 2 summarizes annual electricity generation by technology and country in the fully decarbonised scenario.

In the following, this section goes beyond these findings by presenting disaggregated modelling results for the four endogenously investable energy-storage technologies to inform technology development. As discussed in Section 2, we show results regarding E2P ratios, FCEs, dispatch curves, and prospective markets.

4.1. Analysis of energy-storage E2P ratios, FCEs, and investment costs

The E2P ratio is a key decision variable of our ESM that characterises an energy-storage system. Figure 3 shows the optimal E2P ratios of different energy-storage technologies for each country. The E2P ratios change significantly between the different technologies: the E2Ps of H_2 is between 300 h and 1000 h, of ACAES is between 15 h and 20 h, and of VRFB is between 5 h and 7 h. These E2P ratios depend only weakly on the country. For LIBs, the E2P in solar-rich countries, such as Italy and Spain, is approximately 5 h, whereas it is 2 h–3 h in wind-rich Ireland and Great

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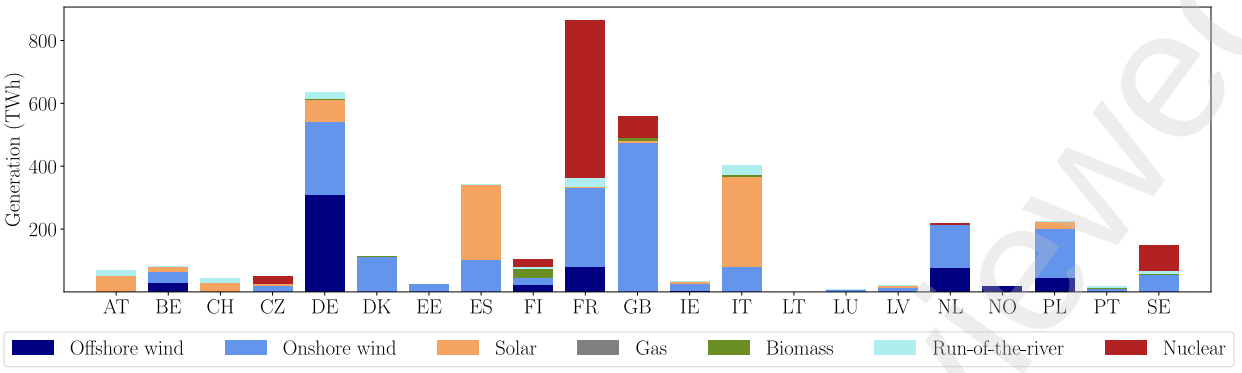


Figure 2: Electricity-generation mix per country.

Britain. Consistent with the findings of Cebulla et al. (2017), different optimal E2P ratios of different energy-storage technologies can be explained by their power- and energy-capacity investment costs. Technologies with relatively low CAPEX for energy capacity and high CAPEX for power have high E2P ratios and *vice versa*. Figure 4 shows a clear negative, non-linear, relationship between optimal E2P ratios and E2P CAPEX ratios, which are defined as $\text{CAPEX}_{\text{energy}}/\text{CAPEX}_{\text{power}}$. The difference between E2P ratios for solar- and wind-rich countries can be explained by the different roles of LIB in these countries: in solar-rich countries, LIB mainly shifts energy from the midday solar peak into the evening hours, while in wind-rich countries LIB mainly balances short-term wind fluctuations to meet demand and minimise electrolyser capacity (which is used to charge H_2 energy storage). This result shows that the underlying system influences the requirements for energy-storage technologies, although the effect is much weaker than the effect of the investment costs power and energy-storage capacity.

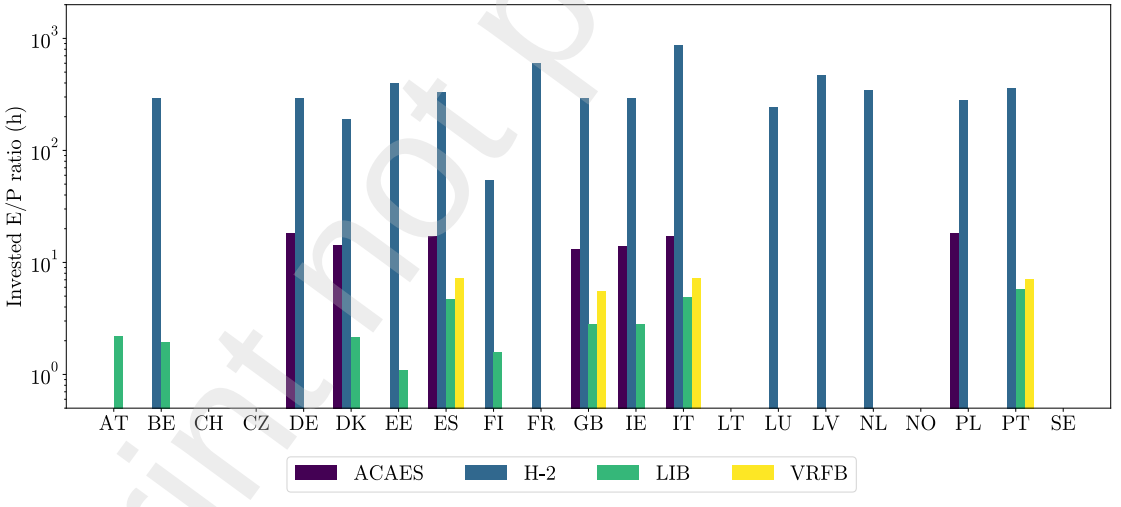


Figure 3: Invested E2P ratio (log scale) per technology and country.

Figure 5 shows FCEs for selected countries and all storage technologies. The figure reveals a strong connection between optimal investment and dispatch decisions, namely an opposite trend of invested E2Ps and dispatched FCEs. Whereas LIB and VRFB have over 200 FCEs per year, ACAES has below 100, and H_2 below 10. Similarly, LIB in solar-rich countries exhibits a higher number of FCEs than those in wind-rich regions. The different FCEs of LIBs between solar-rich and wind-rich countries stem from the different roles that the technology plays in these regions.

These findings can inform technology developers in multiple ways. First, they reveal the inverse relationship between E2P-cost ratios realised in the development and the invested E2P ratios in the optimised system. An energy-storage technology with relatively high (low) E2P-cost ratio (*cf.* Table 1) will likely realise a low (high) E2P ratio in

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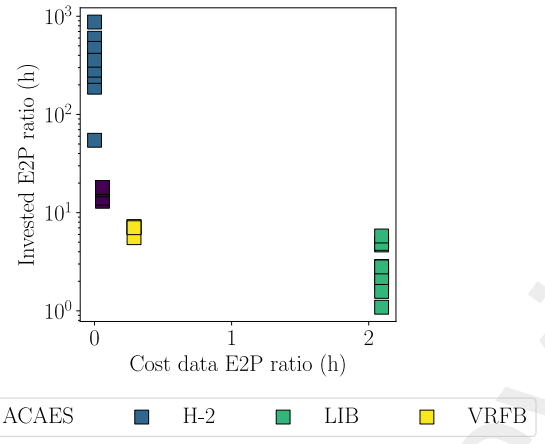


Figure 4: Relationship between invested E2P ratio and E2P-cost ratio across all countries. The horizontal axis shows the ratio of capacity-specific energy cost divided by capacity-specific power cost. Here, capacity-specific means that both the enumerator and denominator comprise annualised CAPEX (*cf.* Table 1) and annual fixed operation and maintenance cost. Only the vertical axis has a logarithmic scale and only four different E2P-cost ratios are attained, due to the spatially homogeneous cost assumptions that are given in Table 1.

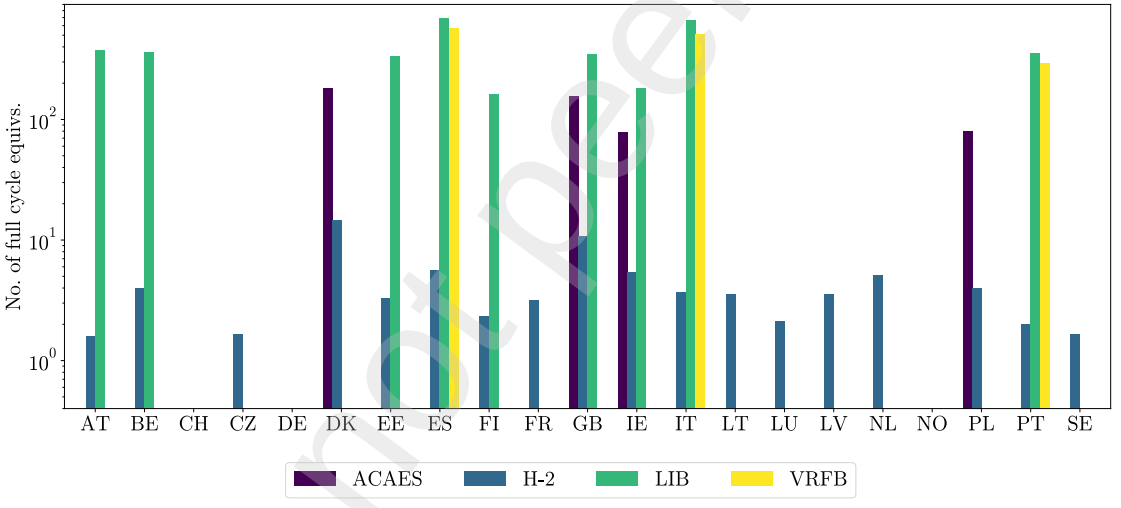


Figure 5: Number of FCEs in the year modelled.

optimal market- or system-based investment decisions. Moreover, such a technology will likely realise a high (low) number of FCEs in optimal market- or system-based dispatch. Conversely, if developers see, for technical reasons, a high potential for an energy-storage technology in realising many (few) FCEs in operation, then it likely needs to be built with a low (high) E2P ratio and must, therefore, be developed towards low power CAPEX (low energy CAPEX). It is important to note that different technologies have inherent limitations to their design and cost structures. For instance, a LiB will never achieve the same energy CAPEX as an H_2 storage.

Secondly, the findings have an important impact on potential business models and the associated risk for energy-storage operators. Energy storage with only few FCEs are reliant upon revenue that is earned during these few FCEs. This means also that they depend strongly on prices and price spreads during only a few periods of time and may be subject to revenue risk if those parameter forecasts are incorrect. Conversely, energy storage with many FCEs have many more opportunities to generate market revenues. For example, energy storage with daily cycles can benefit from daily electricity-price fluctuations between on- and off-peak periods and can generate profits more regularly.

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4.2. Dispatch curves: state-of-charge profiles and associations with residual load

We examine in greater detail the operational role of different energy-storage technologies, beyond the discussion that is presented in Section 4.1. Figure 6 shows time series of the residual load and the state of charge of all four expandable energy-storage technologies for United Kingdom and Spain, which are wind- and solar-rich regions, respectively. Spain's residual-load profile is dominated by the typical intra-day fluctuation of solar irradiation. Conversely, United Kingdom's residual load is dominated by inter-day and inter-week fluctuations in wind availability. Consequently, LIB and VRFB in Spain follow diurnal cycling patterns, thereby exhibiting significantly more and more predictable cycles than their counterparts in United Kingdom. In Spain, the operation of H_2 energy storage is dominated by one seasonal cycle. Conversely, H_2 energy storage in United Kingdom have a great number of smaller cycles, which are related periods with differening wind speeds. ACAES provides flexibility on time scales of days to weeks. Often during solar-rich months in Spain, however, only half of the available H_2 and ACAES capacities are utilised, with energy storage cycling between half-filled and empty. Conversely, LIB and VRFB typically are filled and emptied entirely during each cycle in both countries.

These time series inform developers regarding the operational requirements for energy-storage systems under system-optimal dispatch beyond the aggregated that are FCEs summarized in Section 4.1. The time series provide information on the operational behaviour and changes of different technologies (*i.e.*, frequency of part- as opposed to full-load dispatch), which is important to assess tradeoffs between design-point and off-design efficiencies. For example, Figure 6 shows that LIB in Spain are operated in a quite regular daily cycle, while the operation of the ACAES is much more irregular. The time series provide an indication also of the required energy-storage durations, which can help to assess how self-discharge affects the economic viability of the technologies. Such an analysis is an important step beyond common engineering practice, where calculations rely often on estimated times. Especially for energy-storage systems that contain a thermal element, *e.g.*, ACAES and PTES, such considerations can influence outcomes significantly.

Furthermore, the time series provide insights into the relationship between charging and discharging power and time, which is important for technology developers. For instance, energy storage that charges slowly during 10 h and then discharges rapidly during two hours must be designed very differently compared to one that charges and then discharged during six hours each. Such considerations are particularly important for energy-storage technologies, such as PTES, where the energy-storage size (*i.e.*, the E2P ratio) can be scaled independently given specific charging and discharging components. It is important to note, however, that discharging time and power are connected: when neglecting energy losses, discharging power can be increased with reduced discharging time, or *vice versa*.

4.3. Promising markets: spatial disaggregation and technology associations

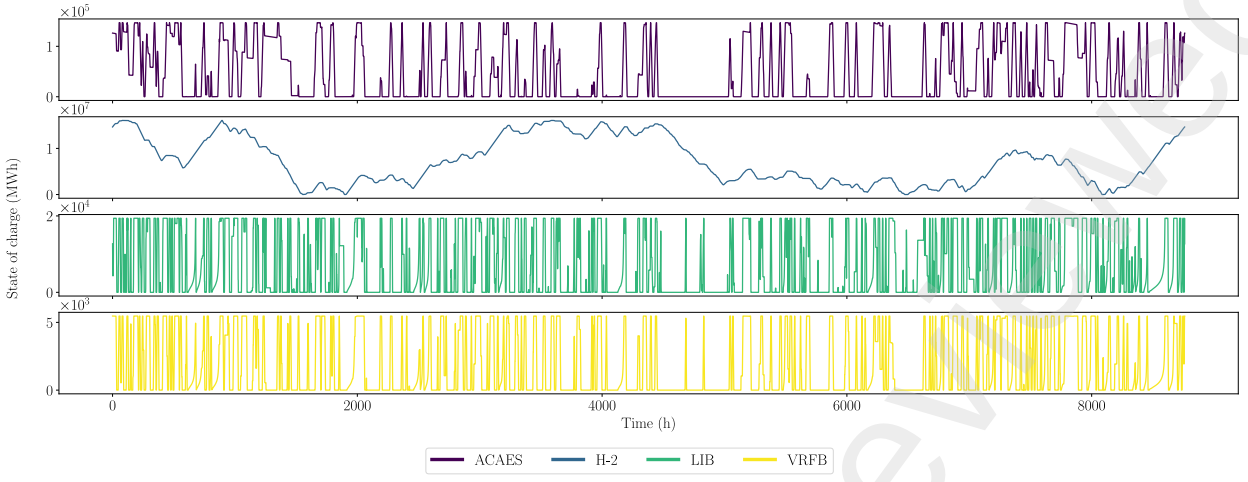
To improve understanding of promising markets for different energy-storage technologies in decarbonised energy systems, we must analyse model results at a national, disaggregated level and in the context of the renewable-energy potentials. Figure 7 summarizes power capacities of energy storage that are built in the countries that are modelled, which are grouped by renewable-energy potentials.[5]

For all wind-rich countries, H_2 is the energy-storage technology with the highest capacity, followed by ACAES or LIB, the capacities of which are mostly one or more orders of magnitude smaller. Conversely, in solar-rich countries LIB has the highest capacities and many different energy-storage technologies are utilised. Further analysis shows that very high PV investments always coincide with high LIB and VRFB investments. Some countries have no or little energy-storage investments, compared to their overall generation capacity. This is due to other technologies providing dispatchable generation (*e.g.*, hydroelectricity for Switzerland, Austria, and Norway and nuclear or bioenergy for Czechia, France, and Sweden). Overall, ACAES and VRFB never dominate national energy-storage capacities and VRFB are built only in solar-rich countries and Great Britain.

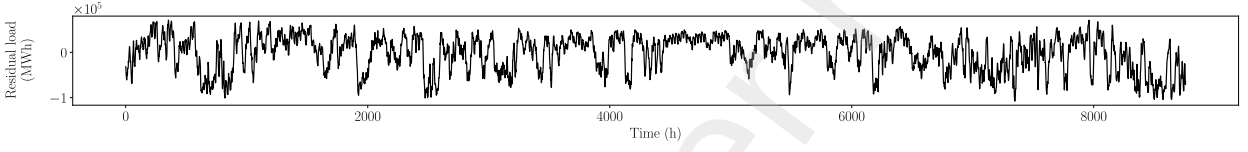
As VRFB is more cost-competitive (on the basis of annualised CAPEX) than LIB for E2P ratios above ≈ 3 h, we attribute the preference of LIB to its 12 percentage point higher efficiency in combination with many FCEs. As an illustrative example, for energy storage with 1 MW and 4 MWh, the annualised CAPEX difference between LIB and VRFB is approximately 8 000 €. An efficiency difference of 12 percentage points causes electricity losses of 168 MWh during 350 FCEs. Therefore, the revenue difference overcompensates financially the CAPEX difference when energy storage can earn an average arbitrage above 48 €/MWh. Such simplified calculations, however, are extremely sensitive

[5] Following Finke et al. (2023), we consider a country to be wind-rich if full-load hours of onshore wind exceed 1500 h/year and offshore wind 4000 h/year, and solar-rich if full-load hours exceed 1100 h/year. According to this classification, France is wind- and solar-rich. Because there is slightly higher wind potential, we classify it as wind-rich in Figure 7 and this discussion.

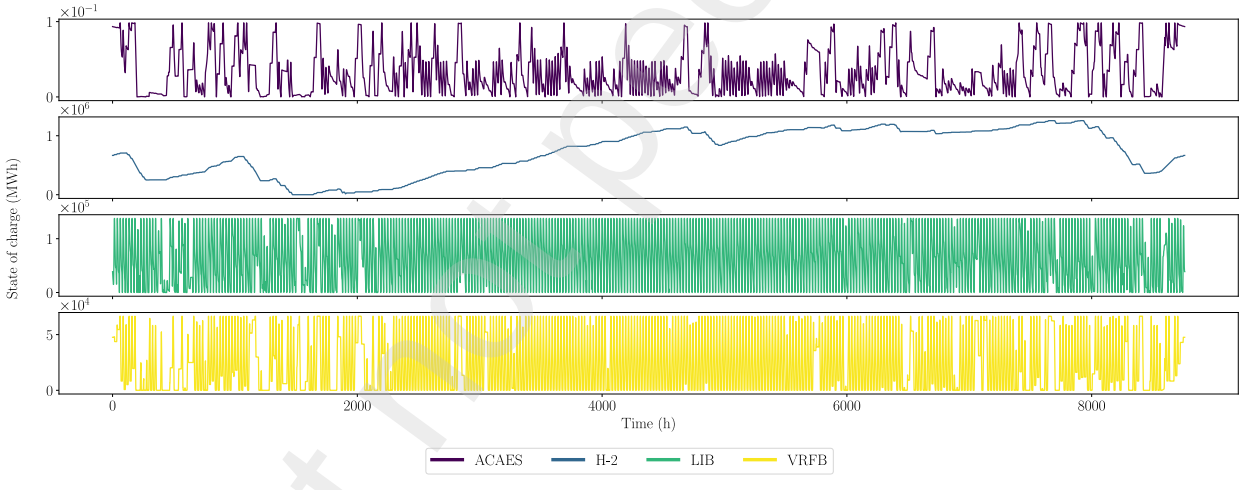
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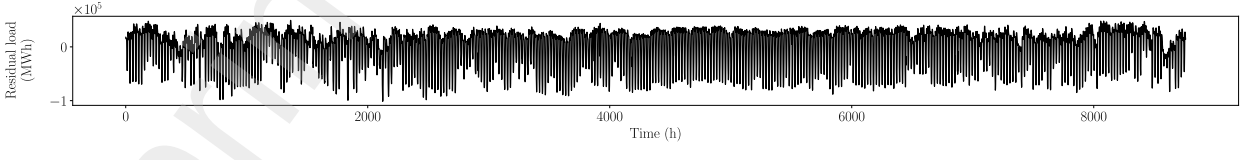
(a) State of charge of all storage technologies in the United Kingdom (wind-rich).



(b) Residual load for the United Kingdom (wind-rich).



(c) State of charge of all storage technologies in Spain (solar-rich).



(d) Residual load in Spain (solar-rich).

Figure 6: Time series for residual load and state of charge of all four energy-storage technologies.

to the underlying assumptions. Similarly, as ACAES is more cost-competitive than VRFB for E2P ratios above six hours (based on annualised CAPEX), our results suggest that the fact that ACAES systems are not built is mainly due to its 11-percentage point lower efficiency. The annualised CAPEX of H_2 energy storage is the lowest of all technologies for

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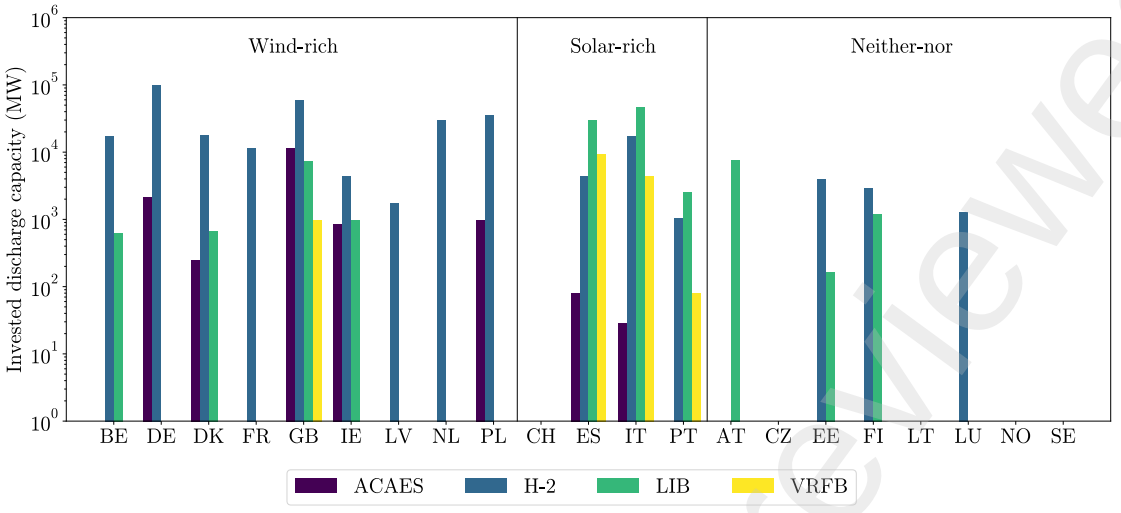


Figure 7: Energy-storage discharging capacities for all countries grouped into wind-rich, solar-rich, or neither-nor countries.

E2P ratios above 10 h when assuming that charging equals discharging power. Consequently, its dominance seems to be explained by its uniquely low costs for large E2P ratios that compensate for its lowest overall efficiency.

This type of analysis enables developers to identify promising target markets for their energy-storage technology while condiering also the previous discussion regarding E2P ratios. For instance, energy-storage developers who consider evolving their technologies towards high E2P ratios of multiple hundreds of hours may find higher potential in markets with high wind availability and low potential for hydroelectricity and other dispatchable generation technologies, as is the case of Germany and Poland. Conversely, developers that aim for E2P ratios that are below 10 h will find greater potential for their energy-storage technologies in markets with high solar deployment, such as Italy and Spain. Such analysis guides more targeted technology development, *e.g.*, towards specific geographical, infrastructural, or regulatory conditions in promising markets. Moreover, strong cost competition between promising low-E2P-ratio energy-storage technologies with high FCEs emphasises the importance of high efficiencies that technology developers must achieve while maintaining cost-competitiveness.

5. Discussion

In this paper, we argue that more collaboration is needed between the ESM and technology-development disciplines. Such collaboration needs to be strengthened particularly for low-TRL technologies, to guide technology development and ensure investments in research and development are well directed. For the case of energy-storage technologies, this paper presents examples of insights from ESMs that typically are not reported in ESM studies, but are valuable for technology developers. In what follows, we discuss key implications and provide insights to technology developers and energy-system modellers in Sections 5.1 and 5.2, respectively, and finally in Section 5.3 we provide a summary of the main limitations of this study.

5.1. Insights for energy-storage developers

First, the LCOS alone is a not a sufficient indicator to provide guidance for energy-storage-technology development. The LCOS is a cost-based metric and lacks an accurate assessment of the revenue potential of energy storage. Moreover, the LCOS depends highly on the assumed utilisation of an energy-storage technology. This paper analyses the use of different energy-storage technologies based on ESM results and finds that the number of FCEs can vary from a few to a few hundred cycles per year. *Ceteris paribus*, this variance can lead to LCOS differing by a factor of 100.

Second, when considering energy-storage revenue, the use of exogenous, static prices overlooks any feedback effects between the technology that is under consideration and market outcomes. In particular, the use of historic prices overlooks the fact that price profiles and price spreads will change fundamentally as a result of the energy transition because of the changes in the technology mix of the underlying electricity system. Although we have

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not analysed revenues in this study, price profiles (proxied by system marginal costs) can be derived from ESMs while considering the changes in the technology mix over time. Therefore, future studies should conduct more sophisticated profitability assessments, considering both technology costs and revenues (*cf.* the works of Finke et al. (2023, 2024b) for two exemplative analyses). Such profiles allow also for assessing the market value of different technologies (Finke et al., 2023). As a further example, such an analysis can quantify expected (additional) revenues from technology improvements to analyse if (additional) costs for such improvements (*e.g.*, larger heat exchangers for thermo-mechanical energy storage) are expected to be compensated by higher revenues.

Third, ESMs generally are capable of providing valuable information for energy-storage-technology development, accounting for dynamic energy-system interactions. ESMs can help identify technology requirements, such as E2P ratios that are needed from a system perspective. Our analysis shows that these may differ by more than a factor of 100, and are driven by energy-storage costs and country. Energy-storage-dispatch profiles from an ESM provide insights into charging and discharging power and speeds, part-load dispatch, and energy-storage durations. Although we do not analyse it in great detail, the ESM results exhibit a range of profiles that are characterised, for instance, by daily cycles with fast and complete (dis)charging or by slow (dis)charging over weeks or seasons and long times with almost full energy storage. While storage durations are important to assess self-discharge and the corresponding impact on overall energy-storage efficiency—particularly in the case of thermo-mechanical storage—(dis)charging speeds are relevant to understand the importance of design-point as opposed to average efficiency. ESMs also can provide insights regarding prospective countries and markets, where market uptake of a certain technology is expected. In particular, the ESM results exhibit associations between favoured energy-storage technologies and favourable conditions for certain renewable energy sources. Moreover, ESMs can inform expected market volumes to assess if the costs of developing a technology can be expected to be recovered during the future.

Finally, to ensure that ESMs provide meaningful guidance to technology development, high-quality, accurate technology characteristics need to be provided by energy-system modellers. This may require multiple iterations, especially in the case of early TRL technologies, where data is either scarce or non-existent, in which case important indicators need to be estimated or predicted. On the one hand, technology costs and efficiencies are key inputs for ESMs. On another hand, as we discuss above, such assumptions depend on energy-storage-dispatch profiles. These are outputs of ESMs and drive, for instance, storage durations with corresponding impacts on self discharge and material choice. These choices affect both energy-storage cost and efficiency.

5.2. Insights for energy-system modellers

ESMs are suitable not only to provide high-level policy support, but also can provide technology-development guidance including for low-TRL technologies. To provide useful support and guidance, however, the way in which ESMs are used needs to be modified. These changes concern both the output side, *i.e.*, the way in which ESM results are presented and the input side, *i.e.*, the way in which model assumptions are prepared and considered in ESMs.

With respect to outputs, as we discuss in this paper, energy-system modellers should focus on presenting more disaggregated results that are useful for technology developers and provide the key information that they require. For instance, total installed capacities—a standard result that is reported in ESM papers—indicate potential markets and market volumes for technologies. More important information, such as dispatch profiles, E2P ratios, expected FCEs, and price profiles or spreads often are missing.

With respect to inputs and energy storage, in particular, it may insufficient to consider LIB as a short-term energy-storage technology and H_2 as a long-term technology. Such a coarse approach risks overlooking relevant gaps concerning required E2P ratios from the perspective of the system and may lead to sub-optimal outcomes. Moreover, it is important to note that ESM inputs, such as technology costs and efficiencies, depend on the dispatch mode of these technologies, which is an ESM output. In other words, using design-point efficiencies may be too optimistic and average efficiencies may be more appropriate. This means that it is insufficient for energy-system modellers to gather such key parameters from engineering publications and use them as static inputs.

Concerning both ESM inputs and outputs, the following points are important. Efficiency and cost estimates from technology developers often have large uncertainties (McTigue et al., 2022). The same is true for almost all other ESM inputs. Therefore, the ESM community should put less focus on presenting theoretical techno-economic optima as model results, and focus more on presenting a set of near-optimal solutions (DeCarolis, 2011; Finke et al., 2024a), highlighting the full (technological) diversity within such a set, *i.e.*, highlighting uncertainty regarding ESM outputs. Such practice also can provide the basis for considering further interests and criteria that are relevant in reality, such as material-supply risks (Colucci et al., 2025) or site availability or public acceptance (Plaga et al., 2024).

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The considerations of such constraints may make a shift necessary to new low-TRL technologies that go beyond the traditionally considered techno-economic sphere. Concerning ESM inputs and outputs, energy-system modellers and technology developers need to collaborate closely. Such collaboration most likely will need to be iterative. Recent research highlights the need for the ESM community to engage with policymakers, investors, and stakeholders in a more participatory way to provide more useful insights and support (McGookin et al., 2024; Esser et al., 2024; Lombardi and Pfenninger, 2025). Such collaboration with technology developers also is important.

5.3. Limitations

As is the case for all model-based studies, there are limitations that are related to both the model and the data that are used. It is important to understand these when interpreting model results. Therefore, we discuss the main limitations, some of which are general limitations of ESMs, whereas others are more specifically pertinent for providing guidance to energy-storage-technology developers.

The study focuses on the electricity sector, assuming exogenous energy demand. This means that sector coupling and any resulting flexibilities, which would compete with energy storage, are not considered. Therefore, exact energy-storage requirements should be interpreted with caution. Only four different energy-storage technologies are considered as investment options in the model, which means inevitably that not all emerging technologies are considered. Moreover, the charging capacities are assumed to be identical to the discharging capacities for all investable energy-storage technologies (except H_2), which may neglect a real-world degree of freedom that technology developers have.

The ESM that is used in this paper identifies a least-cost solution from a central-planning perspective. While in a perfect market, the duality principle guarantees that all energy-storage technologies that are built by the ESM exactly recover their full costs through revenues from the market, there are multiple markets and revenue streams in reality (Lynch and Bertsch, 2025), which may create different business cases (Sioshansi et al., 2022). Moreover, actors' behaviour and revenues may differ in imperfect markets. However, individual actors' decision-making, as considered in agent-based models for instance (*cf.* Ringler et al. (2016) for an overview), is not considered here.

Moreover, the ESM that is used is a linear programme (without integer variables). This makes it hard to distinguish between several small and a few large energy-storage units. From a technology-development perspective, however, this could be an important distinction. While the consideration of integer variables is standard in many ESMs, including Backbone, such variables may yield challenges concerning the computational complexity when considering large real-world systems. In addition, the ESM is deterministic and assumes perfect foresight for a single snapshot year during the future. On the one hand, this means that no pathways or changing technology cost or efficiency assumptions resulting from technological progress over long periods of time are considered. On the other hand, this means that the model does not consider uncertainty. As discussed in this paper, however, an adequate estimation of key parameters, such as costs and efficiencies, for rather distant periods in the future involves very high uncertainties for technologies at all TRLs. Such estimation for low-TRL technologies may not be possible at all.

These limitations call for fundamental research on and development of ESMs to provide improved guidance for the development of emerging technologies. For instance, adopting an inverse-modelling approach seems promising, which determines a Pareto front between technology costs and efficiency as a result, rather than requiring these values as inputs. Methods from multi-objective optimisation can support the determination of Pareto fronts as solutions to optimisation problems with more than one objective. Such an inverse approach would have the potential to indicate priorities for future technology-development activities, *e.g.*, what combinations of costs and efficiency must be achieved to enter the system. Thus, these techniques have the potential to foster closer collaboration between the ESM and technology-development communities.

6. Conclusions and outlook

ESMs are often used to support policymakers, system operators or investors, but fall short of offering guidance to technology developers. This paper has aimed at bridging the gap between ESM and technology development. Focussing specifically on electricity-storage technologies, which are important flexibility sources for the energy transition, we highlight how ESM outcomes can inform the development of emerging technologies. We show ESM results, in particular optimal energy-storage designs and dispatch decisions, for four promising energy-storage technologies in an European case study that seeks to have zero CO_2 emissions before 2050.

We first discuss how optimal invested E2P ratios are reversed to given E2P-cost ratios, *i.e.*, technologies with low-cost power, *e.g.*, LIB, are designed with low E2P ratios whereas technologies with low-cost energy, *e.g.*, H_2, have

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high optimal E2P ratios. We relate this finding to optimal dispatch profiles, showing that low-E2P energy storage have many FCEs, up to the order of one cycle per day for LIB and VRFB, whereas high-E2P energy storage, like H_2, are operated with only a few FCEs per year. Then we discuss temporally disaggregated dispatch decisions, relating FCEs to state of charge and residual-load profiles. We show how typical storage durations and utilisation of the available capacity are related to a technology's E2P ratio and to renewable-energy potentials. Finally, we analyse promising markets for the different energy-storage technologies. We show that low-E2P technologies, such as LIB and VRFB, are used more in solar-rich countries while high-E2P technologies, such as H_2, see greater investment in wind-rich countries. Moreover, we show that for LIB, VRFB, and ACAES, which follow each other as the most cost-competitive technologies with E2P ratios below 10 h, efficiency differences strongly drive the optimal adoption.

We conclude that energy-technology development can benefit greatly from the information that is provided by ESMs, as is shown here for energy-storage technologies. Thus, we demonstrate the benefits of closer collaboration between the disciplines. The model used in this study has many common characteristics and is not fundamentally different from numerous other state-of-the-art ESMs. Certain model features and methodological developments would be beneficial for enabling this form of decision support and guidance for technology developers.

Future work could incorporate greater technological detail (*e.g.*, regarding discrete unit sizes, ramping and start-ups, and sector-coupling) while maintaining or even extending a broad temporal, spatial, and technological scope. Furthermore, when describing early TRL technologies, there is a higher uncertainty in key characteristics (*i.e.*, ESM inputs) such as costs or efficiencies. Therefore, complementary, parallel efforts based on inverse-modelling approaches to inform developers of necessary or desired cost/performance targets would be useful.

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CRediT authorship contribution statement

Valentin Bertsch: Conceptualization, Validation, Formal Analysis, Writing - Original Draft, Writing - Review & Editing, Supervision, Project administration. **Jonas Finke:** Conceptualization, Software, Validation, Data Curation, Formal Analysis, Writing - Original Draft, Writing - Review & Editing. **Katharina Esser:** Visualization, Validation, Data Curation, Writing - Original Draft. **Leonie Sara Plaga:** Conceptualization, Methodology, Software, Validation, Data Curation, Investigation, Formal Analysis, Writing - Review & Editing. **Matthias Mersch:** Formal Analysis, Writing - Original Draft, Writing - Review & Editing. **Jonathan Stelzer:** Writing - Original Draft. **Burak Atakan:** Formal Analysis, Writing - Original Draft, Writing - Review & Editing. **Wolf Fichtner:** Formal Analysis, Writing - Original Draft, Writing - Review & Editing. **Christos N. Markides:** Formal Analysis, Writing - Review & Editing. **Ramteen Sioshansi:** Formal Analysis, Writing - Original Draft, Writing - Review & Editing.

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