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Sodium-ion battery cost projections and their impact on the global energy system transition until 2050

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ABSTRACT

Sodium-ion batteries (SIB) have recently emerged as an alternative to current lithium-ion batteries (LIB), using low-cost and abundant raw materials. However, previous assessments have come to controversial results regarding their economic competitiveness, and the potential impacts of SIB on the wider energy system are still unexplored. This study combines a bottom-up cost modelling including future performance developments on material level for SIB with a global energy system model to obtain a comprehensive assessment of the potential impact of SIB on the global energy-industry transition until 2050. The results show that with recent cost developments and learning curves, batteries are no longer a cost-critical component in the energy system with projected utility-scale battery system capex of 28.5–51.9 €/kWh_{cap} by 2050. SIB potentially outperform LIB on the medium term and are less prone to price spikes and supply shortages. Being a so-called drop-in technology, they could be produced on existing LIB production lines with only minor modifications. Therefore, concerns about supply shortages or price increases can be seen as resolved, since any disturbance in LIB supply would simply trigger a shift to SIB. The overall energy system structure remains virtually unaffected, with similar solar photovoltaic shares, but a shift in power-to-X processes operation. In this sense, electrochemical energy storage is not found to be a limiting factor for the global energy transition. Correspondingly, this work projects the possibly highest stationary battery demand published with a range of 67.9–106.5 TWh_{cap} by 2050, above those in existing cost-optimised energy-industry system analyses.

1. Introduction

Renewable electricity generation has become the new normal, reaching 92.5% in global new power capacity added in 2024 [1,2], dominated by solar photovoltaics (PV), complemented by wind power, and a small share of other power generation technologies. For such increasingly defossilised energy-industry systems, energy storage is a central pillar to ensure flexibility [3,4], with a significant increase in storage demand projected by 2050 [5,6]. In particular, electrochemical energy storage [7] is projected to play a significant role in this development [8,9]. Here, lithium-ion batteries (LIB) with different chemistries are the most mature technology in terms of performance and cost [10,11]. Yet, LIBs are, depending on the selected chemistry, resource-intensive, and require costly materials such as lithium (Li), cobalt (Co), nickel (Ni), and graphite. Consequently, this increasing demand for LIBs raises growing concerns about the security of supply of critical raw materials and the predictability of costs [12–14]. Efforts to reduce reliance on critical materials in LIBs have led to the development of lithium iron phosphate (LFP) batteries [15–17], particularly for applications where maximum gravimetric energy density is not critical, such as stationary storage. However, LFP batteries are still dependent on Li and natural graphite, both of which are categorised as critical raw materials [18–20] and associated with potentially negative social impacts [21,22]. The risk of the Li supply is further increased by its concentration in mainly two regions of the world, Australia and South America [23], and approximately 65% of global Li refining capacity is concentrated in China [24]. For natural graphite, China is the dominating producing country [25].

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Nomenclature

2W/3W	2- and 3-wheelers
BEV	Battery-electric vehicle
BUS	Bus
CAGR	Compound annual growth rate
CAM	Cathode active material
Capex	Capital expenditures
CDR	Carbon dioxide removal
CH_4	Methane
CO_2	Carbon dioxide
Co	Cobalt
DAC	Direct air capture
DC	Direct current
DIS	Disruptive innovation scenarios
e-Hydrogen	Electricity-based hydrogen
e-Methane	Electricity-based methane
E/P	Energy-to-power ratio
ESS	Energy storage system
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
FLH	Full load hours
FTL	Fischer-Tropsch liquids
H_2	Hydrogen
HDV	Heavy-duty vehicles
ICE	Internal combustion engine
IEA	International Energy Agency
LCOE	Levelised cost of electricity
LCOFE	Levelised cost of final energy and non-energy use
LDV	Light-duty vehicles
Li	Lithium
LIB	Lithium-ion battery
LFP	Lithium iron phosphate
LMO	Layered metal oxide
LR	Learning rate
MDV	Medium-duty vehicles
MeOH	Methanol
Na	Sodium
$NaPF_6$	Sodium hexafuorophosphate
NH_3	Ammonia
Ni	Nickel
NiMH	Nickel-metal hydride
Opex	Operational expenditures
PA	Polyanionic
PBA	Prussian blue analogues
PHEV	Plug-in hybrid electric vehicle
PP	Power plant
Prosumer	Producer and consumer
PV	Photovoltaics
RE	Renewable energy
SIB	Sodium-ion battery
SMM	Shanghai Metal Market
SMS	Shared market scenarios
WACC	Weighted average cost of capital

1.1. Sodium-ion versus lithium-ion batteries

In response to the challenges of LIBs, alternative battery chemistries are being explored, with sodium-ion batteries (SIBs) emerging as the most promising post-lithium technology in terms of cost and sustainability [26–28]. This is evident in the latest prototypes of stationary and mobile battery applications, some of which are already based on SIBs. A patent analysis of this field reflects this trend and can be found in Supplementary material 1. Although sodium (Na) and Li possess comparable chemical properties, Na demonstrates higher reactivity and relative atomic mass, along with a larger atomic radius, but possesses lower theoretical capacity compared to Li [29]. Some of the differences between Na and Li have a significant influence on its use in rechargeable batteries. For example, the higher atomic mass of Na and lower theoretical capacity leads to a lower gravimetric energy density of SIBs compared to LIBs, though this performance difference is expected to decrease in the future [30,31].

While SIBs and LIBs share a similar operating principle, they experience notable distinctions when it comes to battery composition. In the following, the central differences are described in detail: First, SIB cathodes, depending on the chemistry, are mainly based on abundant raw materials, whereas LIBs rely on the so-called critical raw materials including Co, Ni, and Li (LPF battery technology relies only on Li and phosphorous as a critical component). The cathode active material (CAM) is essentially based on Na instead of Li and can also be divided into layered metal oxide (LMO) and polyanionic (PA) types. However, a third type of CAM exists for SIBs: prussian blue analogues (PBA) [32,33]. Second, SIBs employ hard carbons instead of graphite as anodes, due to the instability of sodium-intercalated graphite [34,35]. Natural graphite for LIBs is classified as a critical raw material by the European Commission and the US Department of Energy [36,37] with an import reliance of 98% in Europe [36]. The alternative synthetic graphite has a lower initial coulombic efficiency and its production is energy-intensive, of high cost and time consuming [38,39], whereas hard carbons can be produced regionally by a pyrolysis process from very different biowaste types [40], from CO_2 [41], or other methods [42]. Third, instead of using copper as a current collector at the anode as LIBs, SIBs use aluminium as current collectors of both electrodes, as it does not form undesirable alloys with Na at low potentials [43,44]. Using aluminium gives the SIB a weight and cost advantage as aluminium is cheaper and less dense than copper. Fourth, while similar electrolyte formulations to LIBs are possible for SIBs, all variations are based on Na instead of Li, with sodium hexafluorophosphate ($NaPF_6$) as the most prominent variant. Despite the differences in battery composition, the production processes for SIBs closely resemble those of LIBs, and SIBs are therefore often considered a drop-in technology [28]. In fact, most steps in the cell production process, such as coating, drying, calendaring and punching of the electrodes, stacking, packing and electrolyte filling of the cell assembly, as well as formation and degassing of the cell, are identically required for both LIB and SIB cell production [33,45]. The primary difference is the requirement for cell stack vacuum drying, as SIBs are more sensitive to water residues. While LIBs can be dried at a vacuum of a few mbar and still achieve the desired properties, SIB electrode stacks have to be dried under more severe vacuum conditions, potentially increasing energy consumption and manufacturing costs slightly. However, continuous development of cell production processes for both LIBs and SIBs is expected, including technologies that avoid the use of solvents. Advancements such as dry coating would minimise moisture sensitivity and the increased drying requirements. Overall, the similarities in the production process facilitate a potentially seamless transition to the new technology and enables comparable production modelling [43,46].

1.2. Literature review on economic aspects

Since lower costs are one of the claimed key advantages of SIB compared to LIB, Table 1 summarises the available detailed cost assessments of SIBs, together with the corresponding LIB costs. Given the low number of studies assessing the full cell cost, the review includes all possible SIB chemistries. The studies show a wide range of prices, both

Table 1
Literature review of existing cost assessments of SIBs and LFP-based LIBs. Anode of SIBs is hard carbon and of LIBs natural graphite, if not indicated otherwise. Abbreviations: LMO, layered metal oxides; PA, polyanionic.

	Study	Year	Cell cost [€/kWh$_{cap}$]	Cathode material	Data source
SIB	Yao et al. [30]	2024	74; 113	$NaNi_xMn_y(M)_{1-x-y}O_2$ (LMO); $Na_4Fe_3(PO_4)_2(P_2O_7)$ (PA); $NaNi_{0.33}Fe_{0.33}Mn_{0.33}O_2$ (LMO); $Na_{0.67}Fe_{0.5}Mn_{0.5}O_2$ (LMO)	BatPaC [49]
	Zuo et al. [50]	2023	87	$Na_{0.67}[Al_{0.1}Fe_{0.05}Mn_{0.85}]O_2$ (LMO)	BatPaC 5.0 [49]
	Domalanta et al. [51]	2022	88	$NaNi_{1/3}Co_{1/3}Mn_{1/3}O_2$ (LMO)	[52,53], BatPaC
	Hirsh et al. [54]	2020	47	LMO	Not disclosed
	Peters et al. [55]	2019	83	$Na_{1.1}Ni_{0.3}Mn_{0.5}Mg_{0.05}Ti_{0.05}O_2$ (LMO)	BatPaC [49]
	Schneider et al. [53]	2019	157	$NaNi_{1/3}Co_{1/3}Mn_{1/3}O_2$ (LMO)	[52]
	Vaalma et al. [52]	2018	99	β-$NaMnO_2$ (LMO)	BatPaC 3.0 [49]
	Berg et al. [56]	2015	121	$Na_{1.5}VPO_{4.8}F_{0.7}$ (PA)	[57]
LIB	Yao et al. [30]	2024	~77	$LiFePO_4$ (PA)	Not disclosed
	Zuo et al. [50]	2023	54		BatPaC 5.0 [49]
	Domalanta et al. [51]	2022	80		[52,53], BatPaC [49]
	Peters et al. [55]	2019	85		BatPaC [49]
	Wentker et al. [47]	2019	51		CellEst, metalary.com
	Vaalma et al. [52]	2018	102		BatPaC 3.0 [49]
	Berg et al. [56]	2015	105		[57]
	Schneider et al. [53]	2019	113	$LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ (LMO)	[52]
	Hirsh et al. [54]	2020	102	$LiCoO_2$ (LMO)	Not disclosed

for the cathode and for the anode, caused by differences in the research frameworks and underlying assumptions. Consequently, the prices stemming from scientific literature are being compared to current market prices. For LIBs, Table 1 only lists the cost of LFP-based cells where available, even when other chemistries are considered, as LFP is the main competitor for SIBs, especially for stationary applications. In addition, the much-cited study by Wentker et al. [47] is included, even though it does not consider SIBs, as a detailed cost analysis was carried out here.

The higher price of Li compared to Na, even with large fluctuations in recent years, is a primary factor contributing to the higher cost of cathodes in LIBs compared to those in SIBs. Conversely, anodes are less expensive in LIBs and more expensive in SIBs [48]. Overall, LIBs maintain a slight cost advantage at present, considering costs per kilowatt-hour of energy capacity (kWh$_{cap}$), as SIBs generally exhibit lower gravimetric energy density. Emphasising the influence of energy capacity normalisation on overall expenditure is crucial. Further developments in SIBs are expected to alter this cost dynamic in their favour [30].

It can be seen in Table 1 that most studies assessing the cost of both SIBs and LIBs are based on the BatPaC model developed by Argonne National Laboratory [49], which allows for cost modelling of different battery types from a bottom-up approach. However, this reliance on a single model imposes a limitation on the diversity of studies, as the number of different models used is narrower than the number of publications might suggest.

The values provided by the reviewed studies for LIB range from 51 to 113 €/kWh$_{cap}$. Although the values for the same cell chemistry may fluctuate within the same year, often due to the different cost models applied, they are in line with current market prices. There, the latest prices for LFP cells have continuously fallen, with 2024 showing the highest price drop since 2017, to an average cell price of 72 €/kWh$_{cap}$ (78 US$/kWh$_{cap}$) [58]. The prices for LFP cells on the Shanghai Metal Market (SMM) are found to be even lower in November 2024 with around 60 US$/kWh$_{cap}$ including value added tax. A key driver for the current low prices for LIBs is the global manufacturing overcapacity of 3.1 TWh$_{cap}$, which is more than 2.5 times the annual demand of LIBs in 2024 [58]. None of these outlooks yet consider SIBs, except the Roland Berger Battery Monitor [59], which expects SIBs to achieve prices of 46–65 €/kWh$_{cap}$ (50–70 US$/kWh$_{cap}$) in the near future once fully scaled up, with PBA chemistries being the most economic choice [59]. The lack of inclusion of SIBs indicates the need for an up-to-date, bottom-up cost calculation for the battery cells considered in this work. Table 2 shows an overview of current market prices of LFP cells, where for comparability all values are given in €/kWh$_{cap}$, with an exchange rate US$/€ of 1.082, representing the average of 2024.

1.3. Aims and novelties of this study

Although there are a number of studies that look at the cost of SIBs, there is no study yet assessing the impact of SIBs on a global energy-industry system and only one study including a comprehensive projection into the future [30]. This research aims to address this research gap by introducing the following novelties:

- A first-of-its-kind bottom-up approach, ranging from material selection and cell design to the entire battery system and its integration into the global energy-industry system is deployed.
- Scenarios for potential market development are elaborated, considering different raw material prices and performance improvements in SIBs.
- On system level, different combinations of learning rates (LR) for SIBs and LIBs, based on comprehensive literature values, are used to

Table 2
Current market prices of LFP cells. An exchange rate of 1.082 US$/€ is applied.

Source	Pub. year	LFP cell price [€/kWh$_{cap}$]	Ref. year	
Bloomberg NEF [58]	2024	72	2024	Global volume average
Fraunhofer ISI [60]	2024	88	2023	Global volume average
Benchmark Minerals [61]	2023	91	2023	Global volume average
		76	2023	Chinese production
Orangi et al. [62]	2024	79 71	2024 2025	Global average
Shanghai Metals Market (SMM) [63]	2025	60	2024	Chinese production

create scenarios for investment cost projection scenarios covering markets either dominated by SIBs or shared between SIBs and LIBs.

The novel approach includes material and battery development applied to global energy-industry system modelling, policy implications, industry impacts, and system integration to finally assess the global impact of SIBs on energy system structure and whether they could complement or disrupt existing LIB technologies. The results of this study aim to provide an in-depth view on the impact of SIBs and respective cost developments on the overall energy-industry system. These insights will be valuable for shaping battery technology policies and industry directions based on an improved point of view on the role of battery energy storage in the energy-industry transition.

2. Methodology and data

Due to the prospective nature of the present work and the early stage of deployment of SIBs, a bottom-up model to determine the costs on battery cell and the resulting capital expenditure (capex) for the energy storage system (ESS) is applied (Section 2.1). This model is combined with a top-down approach for future cost projection based on a classic LR approach (Section 2.2). Furthermore, the round-trip efficiency of utility-scale batteries is determined based on literature values (Section 2.3), and an explanation of the applied global energy-industry system is provided (Section 2.4).

2.1. Cell-level cost estimation

The battery costs at the cell level are determined via a bottom-up cost analysis based on a modified BatPaC cell dimensioning and cost estimation tool [64]. BatPaC was developed by Argonne National Laboratory [49] to determine the composition and costs of electric vehicle (EV) battery packs for different LIB chemistries based on EV design targets such as available energy and power and the pack layout. However, BatPaC only targets LIB and only allows for the introduction of design parameters on an EV battery pack, but not on a cell level. Though repeatedly used for cost assessment of stationary batteries [50,52], the obtained layouts are not representative for ESS. Therefore, a modification of the BatPaC tool is used [26], expanded by SIB materials allowing for the estimation of LIB and SIB mass balances and costs on cell level. The calculation spreadsheet is provided in Supplementary material 3. To account for the prospective nature of the present assessment, future developments on material level are considered by implementing material key performance parameters for the years 2023, 2027, 2030, and 2035, based on the Batteries Europe key performance indicator projections [65]. Running the BatPaC dimensioning tool for these reference years yields mass balances and cost estimations that reflect the expected technological development for the corresponding years. These bottom-up calculations reflect the foreseen progress on the material level, i.e., performance increases, but no other aspects of cost decrease reflected in classic LR approaches, such as economy of scale effects, efficiency increases, or lower scrap rates. The results for future years thus show only the component of the LRs related with material improvements. Additionally, the estimated prices are naturally subject to intrinsic uncertainty, especially regarding the future development of material costs and performance parameters. While an in-depth uncertainty analysis is beyond the scope of this work, it should be kept in mind when interpreting the results. Hence, these projections are not directly implemented into the energy system model but are used to calibrate the learning curves considering the different developments on material level. This enables the associated uncertainty in battery prices to be considered via a scenario approach in subsequent energy modelling.

Sensitive parameters for the final cell costs are the size of the manufacturing plant and the prices of the raw materials that are required for the battery manufacturing [64]. For the former, a common production capacity of 30 GWh_{cap} per year is assumed for both cell chemistries. Prices for battery cell materials and active materials are retrieved from the SMM, using 5-year average values (2019–2024). For materials that are not available in SMM or similar sources, a simplified estimation based on the precursor material prices and a fixed CAM production cost is used [27]. No material cost projections are used for the BatPaC calculations due to two reasons: (i) global raw material prices forecasts are extremely uncertain given the high volatility of the markets, and (ii) the material price developments are already implicitly considered in the learning curves and the corresponding extreme scenarios. Therefore, only material key performance parameters, but not prices, are projected. The considered cell chemistries are LFP with a graphite anode for the LIB and a PBA cathode in combination with hard carbon on the anode side for the SIB, as it is considered one of the most promising candidates in terms of cost, criticality, and carbon footprint [27]. For both SIB and LIB cells, the same maximum depth of discharge of 85% is considered [67].

Having determined the battery cell costs, the energy-related system costs, i.e., per MWh_{cap} of net energy storage capacity, for the whole ESS are estimated following the approach used in previous studies, assuming a fixed share of the final energy related ESS costs being driven by the battery cells [5]. For utility-scale ESS, typically 75% of the energy-related system costs are driven by the cells, and 25% by the periphery and balance of system components [5,68,69] (excluding the power-related components such as power electronics or cooling), which are separately accounted for and scaled by power requirements, not by energy. These power-related costs (battery interface), which are independent of the energy storage capacity and thus of the cell chemistry, are also, as the operational expenditure (opex), taken from a previous study [5].

2.2. Cost projections of the utility-scale battery market

The future capex of utility-scale stationary batteries are determined via a LR approach and are connected to the bottom-up cost modelling presented in Section 2.1. The LR of stationary batteries is obtained from values in literature. Furthermore, the total capacity of the whole future battery market including stationary batteries, mobile batteries (EVs, etc.), and others (device batteries) is estimated.

2.2.1. Learning rate

LRs represent cost degression as a function of technology deployment, based on the empirical observation that the cost of a technology decreases with a constant fraction with every doubling of historical installed cumulative capacity [70]. Respective LR for battery energy storage are taken from literature. Several levels (cell, battery pack/system) and applications (electronics, EVs, small, utility-scale) of battery storage have to be distinguished. Supplementary material 1 provides an overview of considered literature values. In addition to the reviews by Ziegler and Trancik [71] and Mauler et al. [72], values from Penisa et al. [73], Frith et al. [74], and Yao et al. [30] have been included in the LR assessment. Information obtained from literature on LRs is rather inhomogeneous regarding the level, cell design, and application case. However, Table S2 in Supplementary material 1 gives an overview in what range the LR for batteries is located. On average, the LR of fully usable packs or systems lies between ca. 13.5% up to 20.0% for stationary applications and around 14.3% for mobile applications. For smaller electronics applications, the LR is somewhat higher at 22.5%, however, electronics applications are out of scope for this study. To study the impact of different LRs, three different LR scenarios are chosen based on the obtained values:

Low LR, 12.0%: This scenario reflects a market driven by the stationary residential application and is chosen below the average 13.5% to allow for some higher deviation to the other LR projections. It represents a slowed down cost development due to material and resource bottlenecks for utility-scale batteries.

Realistic LR, 15.0%: Reflecting a market driven by all possible applications. LRs for EV application and utility-scale stationary application of around 14.0–14.3% are rounded up due to the influence of the general LIB storage value of 20.0% and scenario deviation. This scenario represents the base case cost development based on recent years' values for utility-scale batteries.

High LR, 20.0%: Driven by the most optimistic values from literature especially on cell level and reflecting a high LR scenario for the available values for general LIB storage. This scenario represents a deep cost dive for utility-scale batteries due to high scaling and production adaption in the future.

The LR scenarios are used in Section 2.2.4 to obtain the capex values of the future battery market for the economic scenarios.

2.2.2. Battery capacity projection

Estimation of battery capex via LRs requires the projection of installed battery capacities. The total battery capacity must be considered for three main applications: Device batteries for laptops, smart phones, etc., stationary batteries such as residential solar PV prosumer batteries and utility-scale batteries, and mobile batteries for EVs. The projected cumulative installed capacity for all three applications can be seen in Fig. 1.

Electronics and other device capacity between 2000 and 2018 is estimated based on Pillot [76]. Based on the historical trend of the annual growth rate for electronics batteries and a compound annual growth rate (CAGR) of 4% given by Pillot [76], a CAGR of 5% is chosen for future estimation of device batteries. Applied to a total battery capacity of ca. 32.8 GWh_{cap} in 2018, the total sales are estimated to grow to ca. 156.2 GWh_{cap}/a until 2050 with a cumulative installed capacity of ca. 2.9 TWh_{cap} in 2050. Other applications, including household devices and tools, are estimated at ca. 17.8 GWh_{cap} in 2018 and a CAGR of 12% is applied, leading to ca. 668.8 GWh_{cap}/a annual sales by 2050 with a cumulative capacity of ca. 6.2 TWh_{cap}. By 2050, electronics and other devices are estimated to have an annual sales market of ca. 82.5 GWh_{cap}/a with a total sold capacity of ca. 9.1 TWh_{cap}.

Stationary batteries are estimated based on the global energy system modelling results of Bogdanov et al. [5] Stationary batteries consist of residential, commercial, and industrial prosumers, as well as utility-scale stationary batteries. The modelled system is a fully sector-coupled, global energy-industry system, aiming for a 100% renewable energy (RE) system by 2050, following projections of Bogdanov et al. [5]. By this target year, prosumer batteries are estimated to a total cumulative installed capacity of ca. 14.5 TWh_{cap}, and utility-scale batteries at 59.6 TWh_{cap}. In sum, stationary battery energy storage is projected with a cumulative installed capacity of ca. 74.0 TWh_{cap} by 2050.

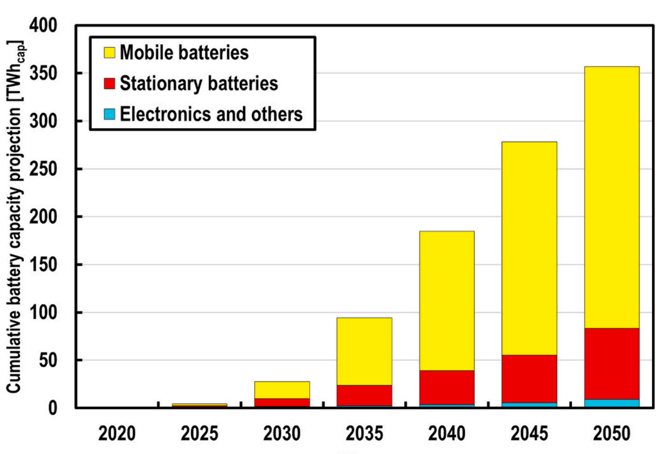

Fig. 1. Projected cumulative installed battery capacity for electronics and others, stationary batteries, and mobile batteries between 2020 and 2050.

Mobile battery capacities have to be differentiated between the road transport segments of light duty vehicles (LDV), 2-/3-wheelers (2W/3W), buses (BUS), medium duty vehicles (MDV), and heavy duty vehicles (HDV). In addition, each road transport segment is divided into four possible powertrains: Battery EV (BEV), fuel cell EV (FCEV), internal combustion engines (ICE), and plug-in hybrid EV (PHEV). Each powertrain is assigned a typical battery capacity per vehicle. With an estimated powertrain share in the total vehicle stock and the total global vehicle stock, the total mobile battery capacity for mobile application can be estimated following the methods in Keiner et al. [77] based on Bogdanov et al. [78]. An overview of parameters is available in Table 3. A detailed calculation breakdown can be found in Table S3 in Supplementary material 1.

In total, the global cumulative installed mobile battery capacity is estimated to ca. 273.7 TWh_{cap} by 2050. The compound annual growth rate (CAGR) of currently 60.4% is in line with present developments, as EV batteries showed annual growth rates of ca. 70% between 2010 and 2020 [79]. The total cumulative battery capacity for all applications is estimated to 356.8 TWh_{cap} until 2050. Mobile batteries have the largest share with 76.7% of total battery capacity, followed by stationary batteries with 20.7%, and electronics and others with 2.6%. Not yet considered are the battery capacities required for battery electric ships and aircraft. The modelled electricity demand from Keiner et al. [77] in 2050 of these ships and aircraft is about 591 TWh_{el} and 633 TWh_{el}, respectively, which may translate to about 1.2 TWh_{cap} if about 1000 full charge cycles per year are assumed. The assumed annual full charge cycles are based on flight and ship interconnection operations and thus with considerable uncertainty. The mobile battery capacities for marine and aviation transportation represent about 0.45% of all mobile batteries. The battery capacity of marine and aviation transportation might be negligible compared to the road transportation mode.

2.2.3. Capital expenditure cost reduction projection applying technological learning

The capex reduction factor c_y of a given year is calculated via the LR approach as used for many similar technologies [80] according to Eq. (1). As mentioned before, the LR describes the change of a reference value, in this case capex reduction, in reference to a change (doubling) in historical installed cumulative capacity. The learning rate as the additive inverse of the experience rate (also progress ratio), however, is assumed to include several key drivers for battery cost reductions.

$$c_y = c_{y-\Delta t} \cdot \left(\frac{Cap_y^{bat}}{Cap_{y-\Delta t}^{bat}} \right)^{\frac{\ln(1-LR)}{\ln(2)}} \quad (1)$$

where $c_{y-\Delta t}$ is the capex reduction of the previous time step, Δt is the time step size of 5 years in this study, Cap_y^{bat} is the cumulative battery capacity of the point in time under consideration, $Cap_{y-\Delta t}^{bat}$ is the cumulative battery capacity of the previous time step, and LR is the LR. Fig. 2 shows the relative capex development with the base year 2025 for the three LR scenarios.

Since the reference capex for SIBs and LIBs are calculated for the 2025 base year (cf. Section 2.1), the relative capex for all LRs is 100% in 2025. Until 2050, the low LR of 12% approaches a relative value compared to 2025 of 44.6%, meaning for this LR the capex in 2050 is 44.6% of the 2025 value. For the realistic LR of 15% the capex decreases to almost a third (35.8%) of the reference value. In case of the high LR the capex decreases to 24.4% of the reference value.

2.2.4. Capital expenditure scenarios

The capex scenarios are divided into two main groups. The first group is the group of disruptive innovation scenarios (DIS). For this group, it is assumed that SIBs are a disruptive technology that are taking over the majority of the battery market by 2050 with a market share of

Table 3
Total mobile battery capacities by transport segment until 2050.

Segment/parameter	Unit	2015	2020	2025	2030	2035	2040	2045	2050
LDV	GWh_{cap}	0	116	1156	9614	36,627	72,406	109,958	131,338
2W/3W	GWh_{cap}	0	11	128	1025	4030	8835	13,877	17,834
BUS	GWh_{cap}	0	8	91	696	2701	5731	8562	10,165
MDV	GWh_{cap}	0	37	426	3310	15,058	32,719	50,619	65,040
HDV	GWh_{cap}	0	33	382	2973	12,162	26,131	39,940	49,280
Subtotal mobile batteries	TWh_{cap}	0	0.2	2.2	17.6	70.6	145.8	223.0	273.7
Compound annual growth rate (CAGR)	%/a			60.4	51.8	32.0	15.6	8.9	4.2

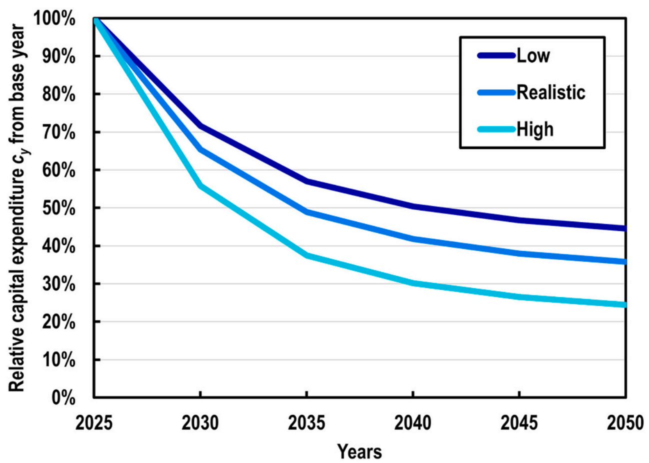

Fig. 2. Capex reduction from the base year 2025 for the three LR scenarios.

90%. LIBs and other battery technologies share the remaining 10% of the market. The second group contains the shared market scenarios (SMS). In this case, it is assumed that SIBs take over 50% of the global battery market by 2050, while LIBs and other technologies share the other half of the market. The transition of the market shares is estimated with a logistic growth according to Eq. (2).

$$p_y^{SIB} = A + \frac{K - A}{1 + 10^{-b\cdot(y-M)}} \tag{2}$$

where p_y^{SIB} is the market share of SIBs in the year of interest y, A is the lower asymptote, K is the upper asymptote, b is the growth rate, and M is the inflection point (the year when the exponential growth turns into a saturation).

For the DIS group, A is equal to 0, the growth rate b is set to 0.16, the upper asymptote K is 0.9 with regard to a 90% market share target, and the inflection point is set to 2035. For the SMS group, the growth rate is set to 0.14, and the upper asymptote is set to 0.5 with respect to a 50% market share target, with an unchanged inflection point. The share of other battery technologies apart from SIB and LIB p_y^{other}, calculated as well with Eq. (2), are assumed to have a market share of ca. 10% in 2020, decreasing to 2% in 2050 mainly due to a shift towards LIB. The lower asymptote is, therefore, set to 0.1, the upper asymptote to 0.02, and a growth rate of 0.14 with an inflection point in 2035 is set, leading to a decreasing s-curve. Finally, the market share of LIBs is calculated with Eq. (3) and the condition according to Eq. (4) is maintained.

$$p_y^{LIB} = 1 - p_y^{SIB} - p_y^{other} \tag{3}$$

$$\forall y \in [2020, 2050] : p_y^{LIB} + p_y^{SIB} + p_y^{other} = 1 \tag{4}$$

where p_y^{LIB} is the LIBs market share and p_y^{other} is the market share of other technologies according to the logistic s-curve calculated as indicated above. Other battery technologies comprise of lead-acid, nickel-metal hydride (NiMH), alkaline, zinc-based, aluminium-based, iron-based, and other cell chemistries.

Each of the DIS and SMS groups contain four sub-scenarios, varying the learning rate of SIBs and LIBs/others. For that purpose, the base capex in 2025 of each technology is multiplied with the relative capex of the respective year (cf. Fig. 2) and the respective market share of the respective year. The combined capex of the battery market of the year y, for scenario s, $CAPEX_y^s$, is calculated according to Eq. (5).

$$CAPEX_y^s = CAPEX_{2025}^{SIB} \cdot p_y^{SIB} \cdot c_{y,LR}^{SIB} + CAPEX_{2025}^{LIB} \cdot \left(p_y^{LIB} + p_y^{other}\right) \cdot c_{y,LR}^{LIB} \tag{5}$$

where $CAPEX_{2025}^{SIB}$ is the capex of SIBs in the base year 2025, $c_{y,LR}^{SIB}$ is the capex reduction factor for year y for the respective learning rate LR applied to SIBs, $CAPEX_{2025}^{LIB}$ is the capex of LIBs in the base year 2025, and $c_{y,LR}^{LIB}$ is the capex reduction factor for year y for the respective LR applied to LIBs. Other battery technologies are assumed with the same capex as LIBs.

The target of this study is to assess the impact of an alternative battery technology to LIBs. An alternative is only economically viable if the capex is less than that of LIBs. Since SIBs have a minorly higher capex in 2025 than LIBs, SIBs have to achieve at least a realistic LR to challenge LIBs in the battery market. This fact is considered in Table 4 for the combination of scenario groups and LRs to obtain the capex scenarios. In short, if LIBs continue with a high capex LR, SIBs do not have a business case. Therefore, such scenarios are not considered.

The starting capex in 2025 are the results of the bottom-up cell cost modelling as presented in Section 2.1. The scaling of the cost from cell level to battery system level is done with a cell/system factor of 0.75, which means the cells represent three quarters of the total battery system capex. Material cost shares of whole battery packs, driven by cell material cost, appear to be in a range of 60–80% [47], and a scaling with 75% validated the bottom-up cell cost modelling with market prices at the end of 2024 for utility-scale batteries.

In addition to the combined scenarios, two additional scenarios are considered to study extreme cases. MIN-Sh as the minimal extreme assumes that only SIBs are installed after 2025, and the capex develop at a high growth rate. MAX-Ll as the maximum extreme assumes that SIBs are not able to gain a foothold in the battery market and only LIBs are installed, but at a low growth rate. The LUT-LitRef scenario represents a literature reference scenario of previous research using the LUT Energy System Transition Model (LUT-ESTM) according to Bogdanov et al. [5], aligned to €$_{2024}$ from €$_{2019}$ with an inflation correction factor of 1.21 [81,82]. Table 4 also presents additional parameters for utility-scale batteries, such as fixed opex, and lifetime. Step-by-step calculation numbers are available in Supplementary material 2.

Different applied LRs serve a different narrative for the market opportunities of SIBs and market developments for LIBs. Realistic growth rates for both battery options mean both technologies have a positive market development without hindrance of cost reductions for any of the two options. With a realistic growth rate of SIBs and a low growth rate of LIBs, a situation is described in which SIBs can continue a normal market development, though LIBs are subject to some obstacles for a continuation with better growth rates, such as bottlenecks or shortages in the availability of resources, foremost Li. Both narrative options are studied for high growth rates of SIBs, to test the case that if SIBs are able to

Table 4
Scenario variations for utility-scale battery capex based on respective market share scenario groups (DIS, SMS) and applied learning rates. Additional parameters relevant for techno-economics applied to all scenarios are mentioned.

Scenario	SIB LR	LIB LR	Capex [$€_{2024}/kWh_{cap}$]					
			2025	2030	2035	2040	2045	2050
DIS-SrLr	Realistic	Realistic	116.3	76.0	56.9	48.7	44.2	41.7
DIS-SrLl	Realistic	Low	116.3	82.3	62.1	50.9	45.5	42.8
DIS-ShLr	High	Realistic	116.3	74.6	50.9	38.2	32.5	29.8
DIS-ShLl	High	Low	116.3	81.0	56.1	40.4	33.7	30.9
SMS-SrLr	Realistic	Realistic	116.3	76.0	56.9	48.6	44.2	41.7
SMS-SrLl	Realistic	Low	116.3	82.6	63.9	54.4	49.5	46.8
SMS-ShLr	High	Realistic	116.3	75.1	53.6	43.0	37.8	35.1
SMS-ShLl	High	Low	116.3	81.7	60.6	48.8	43.0	40.3
MIN-Sh	High		116.5	65.0	43.7	35.2	30.8	28.5
MAX-Ll		Low	116.3	83.2	66.3	58.6	54.3	51.9
LUT-LitRef [5]			184.6	132.7	107.4	91.7	82.1	73.6
Additional parameters								
Opex fixed	SIB/LIB	% of capex	1.7	2.0	2.3	2.5	2.6	2.8
Lifetime (DIS, SMS, MIN, MAX)	SIB/LIB	years	15	20	20	20	20	20
Lifetime (LUT-LitRef) [5]	LIB	years	20	20	20	20	20	20

achieve high growth rates comparable to LIBs in recent years. The rationale behind this investigation is that due to the abundancy of raw materials for SIBs, and SIBs are based on the same technology platform as LIBs, SIBs are less prone to possible bottlenecks in cost development. Therefore, SIBs, while technologically very close to LIBs, might be able to achieve higher LRs compared to LIBs. A total of eleven scenarios aims for a high diversity in possible capex developments. The development of all capex scenarios is depicted in Fig. 3.

The variation of the market shares and LRs leads to a diverse group of scenarios, with capex between 28.5 $€/kWh_{cap}$ and 51.9 $€/kWh_{cap}$ by 2050. Due to the phase-in of SIBs starting with a market share of 0% in 2025, the minimum values of the MIN-Sh scenario are not approached until 2040, when, after the infliction point in 2035, high market shares and high LRs of SIBs significantly drive down the capex. Scenarios of the SMS group start on average with lower capex, in the early years of the transition period, but at least 50% market share of SIBs avoid very low-cost utility-scale batteries compared to the DIS scenarios. The LUT-LitRef scenario is consistently outperformed over time and is unable to reach the capex based on the new revised estimation. These cost assumptions are applied for utility-scale battery energy storage. Smaller prosumer-scale batteries are not adapted.

2.3. Battery round-trip efficiency

The round-trip efficiency of battery systems varies with ambient temperature due to cooling requirement and type of operations. For instance, batteries installed for frequency control regulation that are used with high C-rates show a lower round-trip efficiency than batteries used as energy storage or peak shaving [83]. Specific values from battery manufacturers in data sheets, etc. are, therefore, hard to obtain. Literature values are also rather scarce, however, values and ranges are available, as depicted in Fig. 4.

All of the sources explicitly focus on LIBs. Table 5 presents the numeric values of round-trip efficiencies found in literature and specific contexts of the numbers to further classify the findings shown in Fig. 4. The context is important when choosing a round-trip efficiency value for further modelling, as there are important differences to be considered when assessing values from literature.

The overview shows that numbers for the round-trip efficiency of grid-connected utility-scale LIBs are around 90%, especially if DC efficiency values and values for an explicitly mentioned frequency control regulation application are excluded. It is assumed that most of the numbers below 90% are based on first batteries installed with low energy-to-power (E/P) ratios used for frequency control regulation. The difference in round-trip efficiency is clearly described by Parlikar et al. [83]. Therefore, with a future focus of batteries towards energy storage, with higher E/P ratios, lower average C-rates, and development beyond demonstration phase, a round-trip efficiency of 90.0% is chosen for the year 2025. By 2050, this value is assumed to increase linearly by $0.6\%_{abs}$

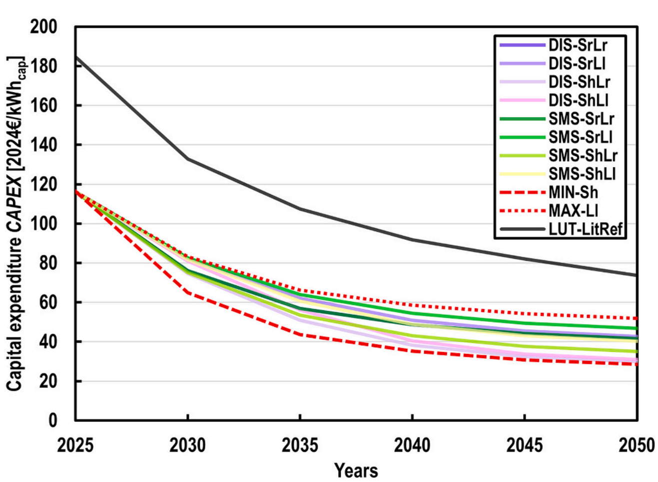

Fig. 3. Capex development of all scenarios from 2025 until 2050.

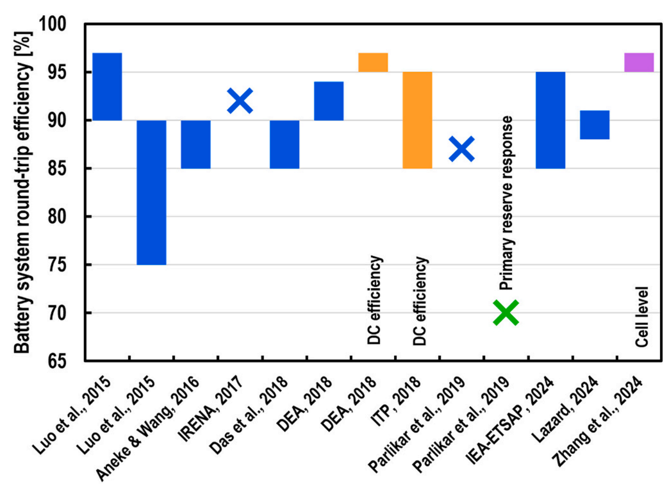

Fig. 4. Literature values obtained for battery system round-trip efficiency. Special cases such as direct current (DC) efficiency, batteries used for primary reserve response, or efficiency on cell level are marked accordingly as mentioned in the study itself, not in the primary source.

Table 5
Source, publication year, round-trip efficiency value range and context and notes of the findings shown in Fig. 4.

Source	Publication year	Round-trip efficiency [%]	Context/note
Zhang et al. [84]	2024	95–97	Cell level; includes several LIB and SIB technologies
Lazard [85]	2024	88–91	Residential and utility-scale LFP and NMC batteries
IEA-ETSAP [86]	2024	85–95	For time scale 2020–2050 and technology readiness level 9 LIBs
Parlikar et al. [83]	2019	87.0	Utility-scale LIB used for peak shaving
		70.1	Utility-scale LIB used for primary reserve response
ITP [87]	2018	85–95	DC round-trip efficiency based on 10 different battery packs tested
DEA [88]	2018	90–94	90% lower uncertainty limit in 2020, 94% upper uncertainty limit in 2050; NMC battery for grid-scale storage; AC
		95–97	95% lower uncertainty limit in 2020, 97% upper uncertainty limit in 2050; NMC battery for grid-scale storage; DC
Das et al. [89]	2018	85–90	LIB; demonstration phase
IRENA [68]	2017	~92	LFP battery electricity storage system
Aneke and Wang [90]	2016	85–90	LIB; demonstration phase
Luo et al. [91]	2015	90–97	Pre-2010 source; demonstration phase; LIB
		75–90	LIB; primary source states 75–90% for fast frequency control, 90–94% for utility-scale, 80–93% for commercial and industrial, 75–93% for distributed applications; demonstration phase

per 5-year time step to 93.0%, reflecting technological improvement based on DEA [88].

2.4. Global energy system transition modelling

The energy system transition modelling to study the effects of the different battery storage capex as presented in Section 2.2.4 is done with LUT-ESTM [5,92]. A schematic overview of the model and flow diagram is shown in Fig. 5. A more detailed model description can be found in Supplementary material 1. The simulations are done in hourly resolution to rightfully account for variable characteristics of RE sources, in particular solar PV and wind power. This temporal resolution is required to study the requirement for respective energy storage demand in sufficient detail. The modelling approach is a best policy scenario, aiming for a comprehensively sector-coupled, highly renewable energy system by 2050.

The model includes all relevant RE sources for electricity generation such as solar PV (fixed tilted, single-axis tracking, monofacial, bifacial, vertical, offshore floating), wind power (onshore, offshore), hydropower (run-of-river, reservoir), wave power, geothermal, and concentrating solar thermal power. Conventional power plants (PP) are included as well as combined heat and power (CHP) plants. Conventional fuels for PPs and CHP in the form of steam turbines may be hard coal, lignite, or nuclear. ICE generators may be powered by oil or oil products, and gas turbines are powered mainly by natural gas or electricity-based methane (e-methane) or electricity-based hydrogen (e-hydrogen) in later years of the transition. PPs and CHP plants may also be powered by biomass, which is limited to sustainable sources such as forest and agricultural residues.

In addition to batteries as energy storage (prosumer, utility-scale, vehicle-to-grid), pumped hydro energy storage and adiabatic compressed air energy storage are included as direct electricity storage technologies as well. Further storage technologies are hydrogen (H_2) energy storage, methane (CH_4) energy storage, and thermal energy storage. Heat conversion technologies comprise of biomass, fossil fuel, and gas heaters, as well as power-to-heat transformers such as heat pumps and direct electric heating via heating rods.

CO_2 to produce e-fuels and electricity-based chemicals (e-chemicals) for the chemical industry (liquid fuels, e-methanol, e-methane, e-ammonia) can either be supplied by direct air capture (DAC) or point source capture from PPs or industry point sources, e.g. cement or pulp and paper industries. The carbon dioxide removal (CDR) sector [93] would also be mainly supplied by DAC or biomass-based point source capture, though the CDR sector is not considered in this study. Desalinated water is supplied via seawater reverse osmosis plants. The portfolio of power-to-X technologies include all relevant options required for a Power-to-X Economy [94]: power-to-heat transformers (cf. above), seawater desalination [95], electrolyser (e-hydrogen, various applications) [96,97], Haber-Bosch synthesis (e-ammonia for transport and chemical industry, fertiliser) [98,99], methanol synthesis (e-methanol for transport and chemical industry) [100,101], Fischer-Tropsch synthesis (liquid e-fuels for transport) [101,102], methanation (e-methane for heat production and power balancing) [97,102]. Furthermore, electrified industry processes for power-to-steel [103] and power-to-aluminium are included.

The modelling framework of LUT-ESTM starts by input data preparation. The techno-economic parameters include capex, fixed opex, variable opex, and lifetime for all technologies, fuel cost for all fuels applied, and weighted average cost of capital (WACC). Technical parameters are conversion and charge/discharge efficiencies of all relevant technologies, as well as relative energy demand (power, heat, materials, etc.) of conversion processes of e-fuel production and industry. The power, heat, transport, industry, and desalination demand are modelled with the bottom-up energy demand modelling tool LUT-DEMAND [77,104] applying the LUT Late Economic Equality Scenario (LUT-LEES) and United Nations medium population estimation (UN medium) as the macro-economic basis. Demand inputs are available in Supplementary material 2. Furthermore, generation and demand profiles are provided, as well as existing power and heat generation capacities, which are the basis of each time step of the transition simulation and are used until their end of life. Restrictions and constraints regarding the transition scenario are provided as well.

In the second step, the prosumer sub-model is run. This model has the objective to optimise the cost of energy supply of distributed and individual producers and consumer (prosumer), affecting the respective residual demand for power and heat of the overall energy system. The adapted demand numbers are fed together with all other inputs to the main energy system transition model with the target to optimise the annualised energy system cost. In the last step, the results of the system transition are processed for result presentation.

As mentioned above, LUT-DEMAND is a bottom-up model. The energy demand is modelled on country-level, and then aggregated to different region levels. The simulation of this study done with LUT-ESTM is done for nine major regions, as depicted in Fig. 6.

Each of the nine major regions is treated as its own entity with no interconnections between major regions assumed. Individual major region modelling enables a more in-depth view of the impact of different battery capex scenario on the overall energy system for different climatic regions globally. The results, however, will be presented in total global values, though they are available on major region level in Supplementary material 2. The resource profiles are formed on the 151 LUT region level as shown in Fig. 6 and then aggregated to the nine major regions to avoid lumping of resources [105] in one corner of the region while in reality resources will be installed more distributed among the regions within a major region. This aggregation ensures more realistic

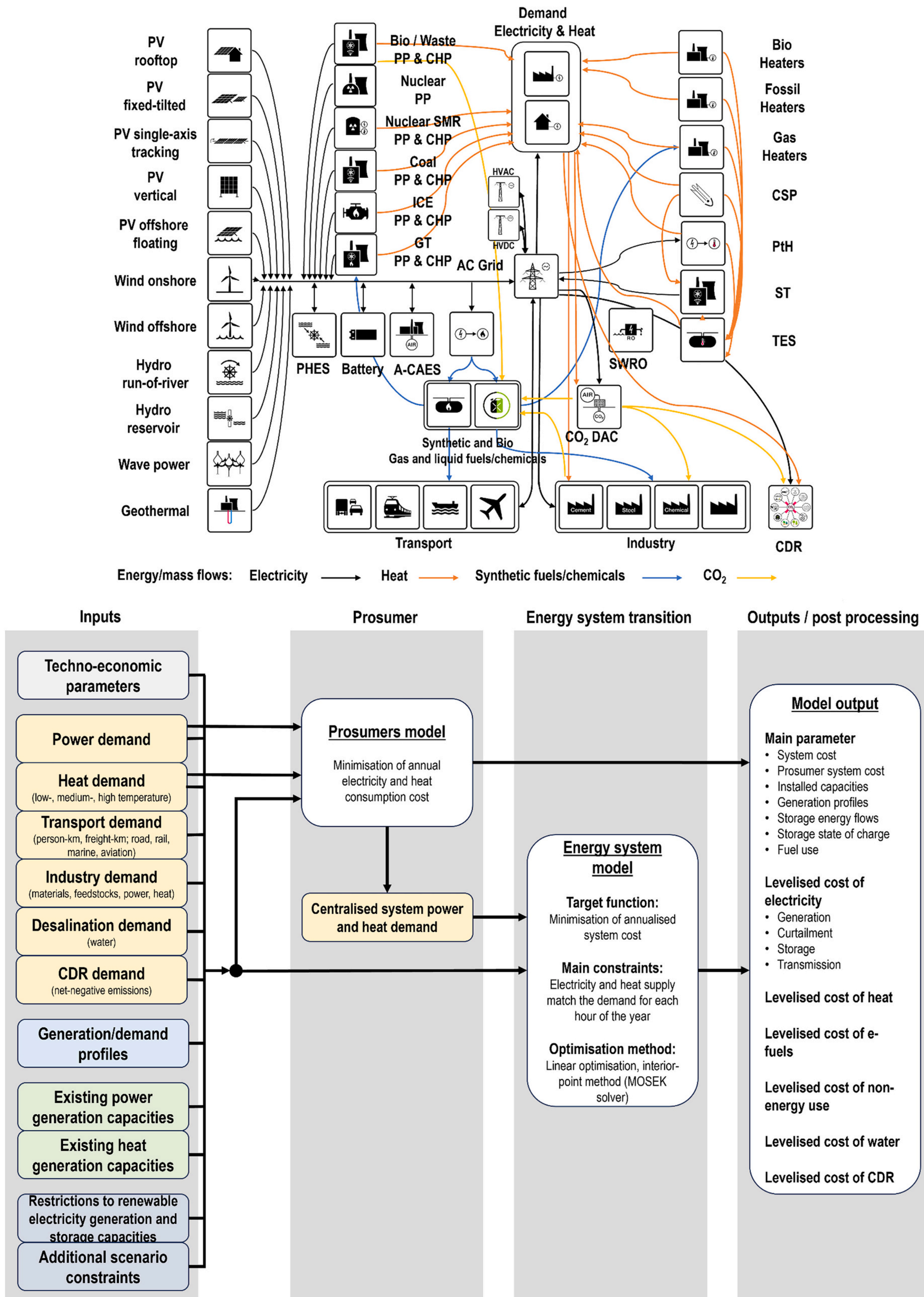

Fig. 5. Schematic overview of technology interconnection with electricity, heat, fuel/feedstock, and CO_2 flows (top), and flow diagram of the four-step modelling framework of LUT-ESTM with process inputs, prosumer modelling, energy system transition, and outputs/post-processing (bottom).

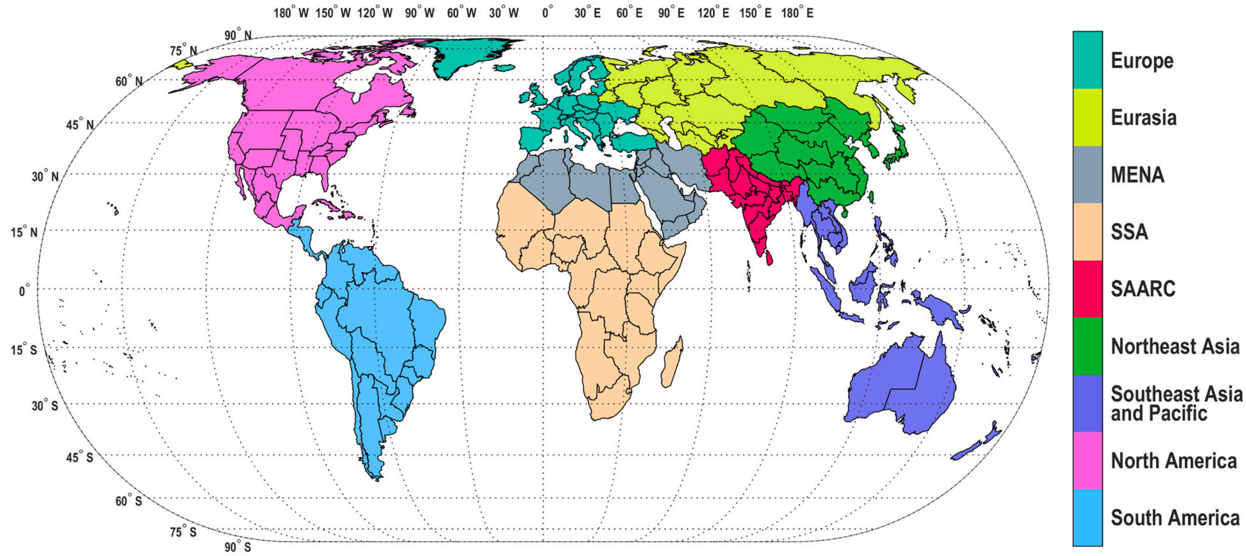

Fig. 6. Major regions of the LUT-ESTM tool considered in this study in spatial breakdown. The regions shown are on the level of 151 LUT regions as an intermediate step between country resolution and major regions.

characteristics of available RE sources.

3. Results

The results in this study comprise of sodium-ion and lithium-ion cell costs (Section 3.1), cost on battery system level (Section 3.2), and energy-industry system impact (Section 3.3).

3.1. Cell-specific cost for sodium-ion and lithium-ion batteries

The prices for the SIB and the corresponding LIB cells as obtained from the bottom-up cost modelling are provided in Fig. 7. For the LFP cells, these are situated at 93 €/kWh_{cap} in 2023, well in line with latest cost analyses [30,60–62,106]. The prices decline until 2035 due to performance increases on material level to 82 €/kWh_{cap}. This cost is higher than current prices stated in SMM (around 60 US$/$kWh_{cap}$), but it is given per kWh of useable energy capacity for a maximum discharge depth of 85%, not for a hypothetical complete discharge until 0% state of charge, which would be detrimental to the battery cycle life. For SIBs, the corresponding cell-level prices are also around 93 €/kWh_{cap} in 2023, but show a stronger cost decrease, reaching 79 €/kWh_{cap} in 2035. Also, the projected developments only capture the component of improvements on material performance level, i.e., energy density on cell level. Historically, these make up around 17% of the overall learning curve [62], while the remaining drivers for cost decreases, such as improvements in efficiency, utilisation rates, reduced scrap rates, economy of scale, etc. are not captured by the bottom-up model. It should be noted that these values are only point estimates based on the material costs and performance parameters described in Section 2.1, and are, therefore, associated with significant uncertainty. Still, based on the projected performance evolution of both battery chemistries, SIB are expected to show a stronger price decrease even if holding all other aspects constant, suggesting a higher LR for SIB. The main driver of this is the expected progress in the specific capacity of CAM, which is more pronounced for SIBs. On anode active material this effect is also significant with smaller differences between SIB and LIB. However, other possible factors, such as the introduction of new technologies, are not considered in the underlying KPI estimations [65] and are therefore not included in the present cost estimates. With the performance parameters for the year 2023, the price of SIB on cell level is at level but decreases continuously until 2035 (the latest year for which performance KPI are provided) to 96% of the corresponding LIB costs. The SIB used here for comparison is based on PBA, as these offer the highest potential lifetime. Although the estimated prices for other SIB chemistries (nickel-based layered oxides and vanadium-based polyanions) are lower, these chemistries typically offer shorter lifetimes, which is detrimental to their use in ESS. The corresponding values are provided in Supplementary material 3.

When looking at the cost breakdown to battery cell components (Fig. 8), the main cost drivers are the materials, making up around 65% of the total costs for SIB and almost 70% for LIB. Of those, the highest differences between SIB and LIB can be identified for the CAM and the current collectors (aluminium vs. copper). Here, the SIB has a clear advantage, and its sensitivity on material price fluctuations will also be lower, apart from showing historical raw material prices lower price volatility for SIB raw materials [50]. On the other hand, the cost advantage of the SIB is limited by the higher volume (and thus mass) of electrolyte, which is directly driven by the lower gravimetric density and thus thickness of the PBA CAM.

3.2. System cost for sodium-ion and lithium-ion batteries

Based on the battery cell costs, the capacity-related capex for the whole ESS in the starting year 2023 are estimated to be 124 €/kWh_{cap} for both the LIB and the SIB system, decreasing to 110 and 105 €/kWh_{cap} by 2035 for the LIB and SIB, respectively (see Table 6). Considering similar lifetimes and degradation rates, these cell costs equal 1238 and 1243 €/MWh_{cap} delivered for a system with a lifetime of 20 years and 10,000 cycles in 2023 and 1096 and 1051 €/MWh_{cap} in 2035. The observed spread in prices is attributable only to the expected progress in terms of performance (KPI). The total learning rates can therefore be expected to differ between LIB and SIB, with the SIB showing higher cost degression coefficients. Regarding battery lifetime, no reliable field data is yet available for SIB and their lifetime therefore is assumed to be identical to that of LFP [26,43].

The power-related capex (battery interface) is obtained from literature [5], situated at 135 €/kW in 2023. This value is at the lower end of battery interface capex indicated by other studies ranging between 150 and 400 €/kW [67,69,107], but corresponds with the percentual share indicated for a typical E/P ratio of 4 h battery for the final system [68] and observed market prices. In any case, the battery interface is independent of the cell chemistry and of corresponding differences in performance development, so it will not affect the cost ratio between the SIB and LIB chemistries.

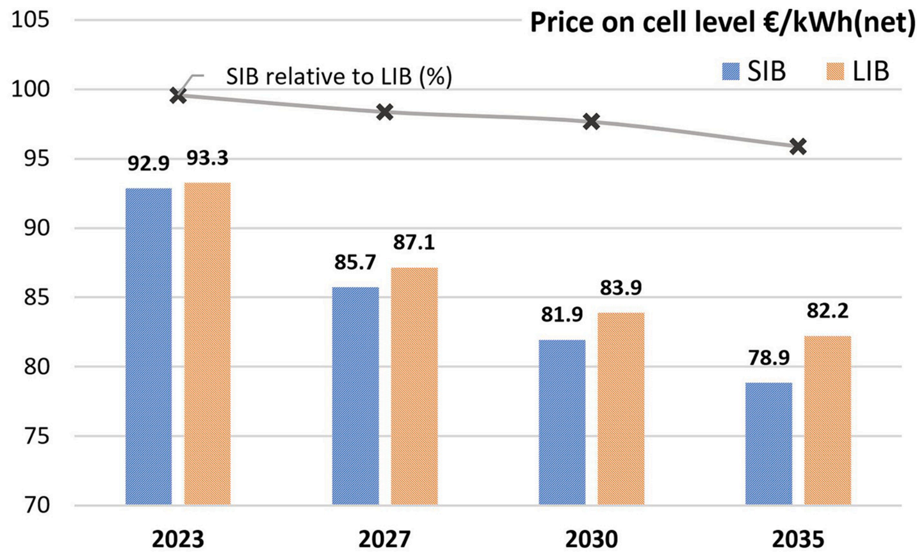

Fig. 7. Estimated price trends for SIB and LIB due to advancements in performance. Note that years on x-axis are not equidistant.

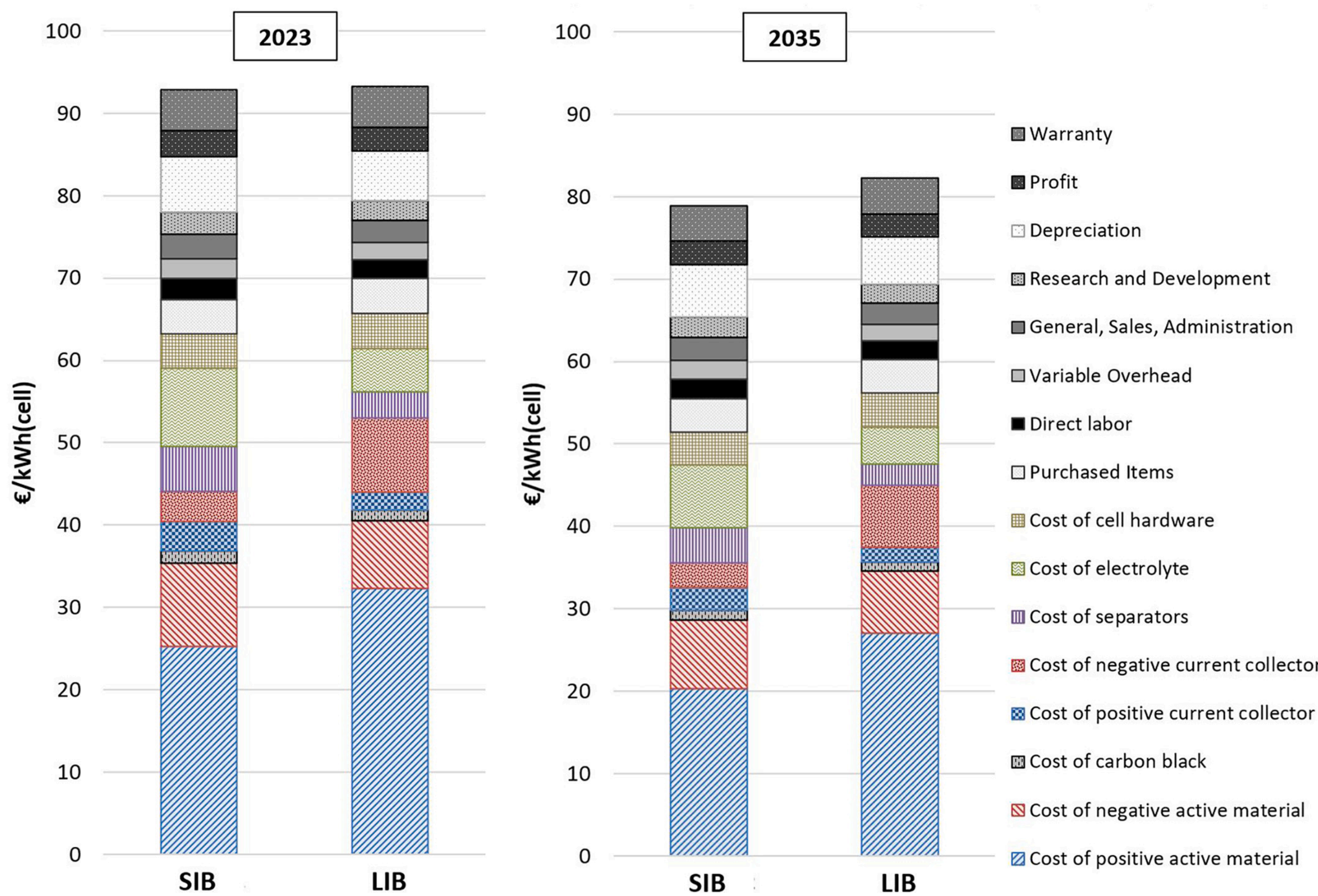

Fig. 8. Break-down of costs to cell components for 2023 (left) and 2035 (right).

3.3. *Global energy system impact of battery capital expenditure scenarios*

With the given cost assumptions for battery packs and respective scenarios as obtained in Section 2.2, the impact of different battery capex scenarios on the energy system structure and cost can be evaluated; respective results are presented in this subsection. Key results are the battery energy storage capacity in combination with solar PV, wind power capacities, the impact on the operation of synthesis units, and the overall economic impact. For the sake of conciseness, this subsection presents only global aggregated results. Regional numeric results are available in Supplementary material 2.

Table 6
Projected system level cost degression due to increases in performance (only considering cost decrease due to performance improvements, no real learning curve).

			2023	2025	2027	2030	2035
SIB Battery storage	Capex	€/kWh$_{cap}$	124	121	114	109	105
		rel to LIB	100%	99%	98.5%	98%	97%
LIB Battery storage	Capex	€/kWh$_{cap}$	124	121	116	112	110

3.3.1. Battery energy storage capacity and core renewable energy sources

Batteries as short-term energy storage are mainly associated with solar PV and less with wind power. However, by a possible impact on the solar PV capacities, wind power capacities might be indirectly affected. Fig. 9 shows the cumulative installed capacities of batteries, solar PV, and wind power until 2050 among all scenarios.

A clear dependency of battery capacities on the scenarios can be noticed. It can also be seen that by mid-century utility-scale batteries dominate the total installed battery capacities. Since small-scale prosumer battery capex have not been varied, the additional battery capacities for prosumers are the same for all scenarios. The lowest battery capacities are installed for the LUT-LitRef scenario with up to 36.1 TWh$_{cap}$ until 2050. On the contrary, the minimum extreme case scenario, MIN-Sh, installs about 2.4 times as much utility-scale batteries with a total capacity of up to 87.8 TWh$_{cap}$ until 2050. Therefore, the installed utility-scale battery capacity is almost linearly related to the capex difference, since the capex of the LUT-LitRef scenario is about 2.6 times that of the MIN-Sh scenario in 2050. The same relation can be noticed for all other scenarios as well. The MAX-Ll scenario as the other limiting scenario among the new scenarios reaches a cumulatively installed battery capacity of 49.2 TWh$_{cap}$ in 2050, ca. 1.4 times that of the LUT-LitRef scenario while the latter has a ca. 1.4 times higher capex until 2050. Including prosumer batteries, the total installed stationary batteries reach 54.8 TWh$_{cap}$ for the LUT-LitRef scenario, and between 67.9 TWh$_{cap}$ for the MAX-Ll and 106.5 TWh$_{cap}$ for the MIN-Sh scenarios.

Solar PV capacity does not react strongly to different battery capacities. Overall, the solar PV variation among the scenarios is only minorly affected. The lowest cumulative solar PV capacity occurs for the LUT-LitRef scenario at 95.2 TW$_p$ until 2050. The highest installed solar PV capacities occur for the DIS-ShLl and SMS-SrLr at 99.2 TW$_p$. Therefore, the total solar PV capacity increases only by ca. 4.2% compared to the LUT-LitRef scenario. Interestingly, the highest solar PV capacity cannot be seen for the scenario with the lowest battery capex by 2050. The two extreme cases, MIN-Sh and MAX-Ll, pose middle-of-the-road scenarios in terms of solar PV capacity installations until 2040. The reason for that is a combination of several circumstances, which will be presented in the following subsections.

The variation of wind power capacities among the scenarios is, however, more pronounced. Especially after 2030, the installed wind power capacity varies noticeably. The lowest wind power capacity by mid-century occurs for the DIS-SrLr at 13.9 TW. Out of the new scenarios, the SMS-SrLl installs up to 16.2 TW until 2050. The LUT-LitRef scenario relies the most on wind power with an installed capacity of 17.1 TW. Compared to the literature reference, the wind power capacity decreases in all new scenarios up to 18.4%.

With solar PV and wind power being the most important RE sources of the future, these results indicate a shift towards a higher use of solar PV electricity. However, since solar PV capacities do not increase significantly, the combination of steady solar PV capacities, higher battery capacities, and lower wind power capacities indicate a demand response of solar PV electricity use. Lower cost batteries seem to take over directly consumed electricity to shift more electricity from day to night, decreasing the need for wind power.

3.3.2. Impact on operation of synthesis units

The most important flexibility option of power-to-X processes is the electrolyser. Fig. 10 shows the installed electrolyser capacities and the full load hours (FLH) of the electrolysers.

Total electrolyser capacities across the majority of scenarios do not differ significantly. The only outlier scenario can be identified as the MIN-Sh scenario with up to 22.7 TW$_{el}$ installed electrolysers until 2050. All other scenarios, including the LUT-LitRef scenario, lie in a relatively close range between 24.6 TW$_{el}$ (DIS-ShLl) and 27.6 TW$_{el}$ (LUT-LitRef). By looking at the FLH, it can also be seen that the mode of operation only differs for the MIN-Sh scenario. Low FLH mean that the electrolysers are used more flexibly, following the availability of RE. FLH of close to the hours of the year (8760) indicate a baseload operation. As expected, when the energy system shifts towards variable RE sources and electrolyser become cheaper, the FLH of electrolysers start to decrease from 2030 onwards. This shift happens for all scenarios except the MIN-Sh very uniformly and variations are minimal. Until 2050, electrolyser FLH decrease to ca. 4400 in case of the MIN-Sh scenario and for all other

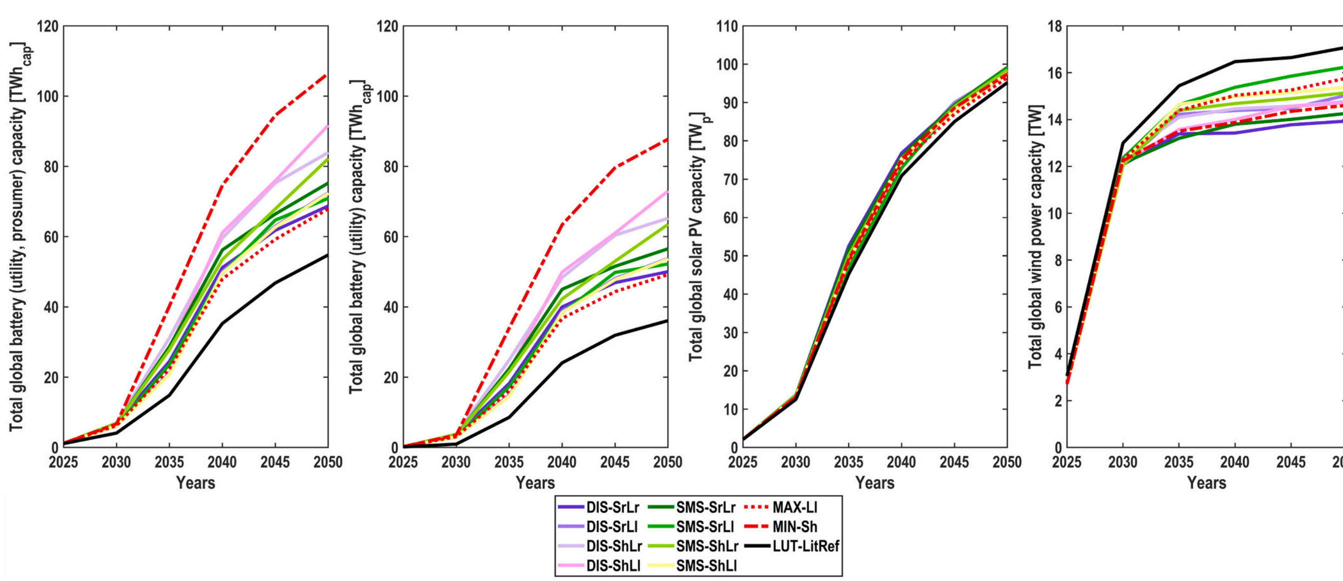

Fig. 9. Cumulative installed capacities of all batteries (prosumer and utility-scale, top left), utility-scale batteries (top right), total global solar PV capacity (bottom left), and wind power capacity (bottom right) among all scenarios from 2025 until 2050.

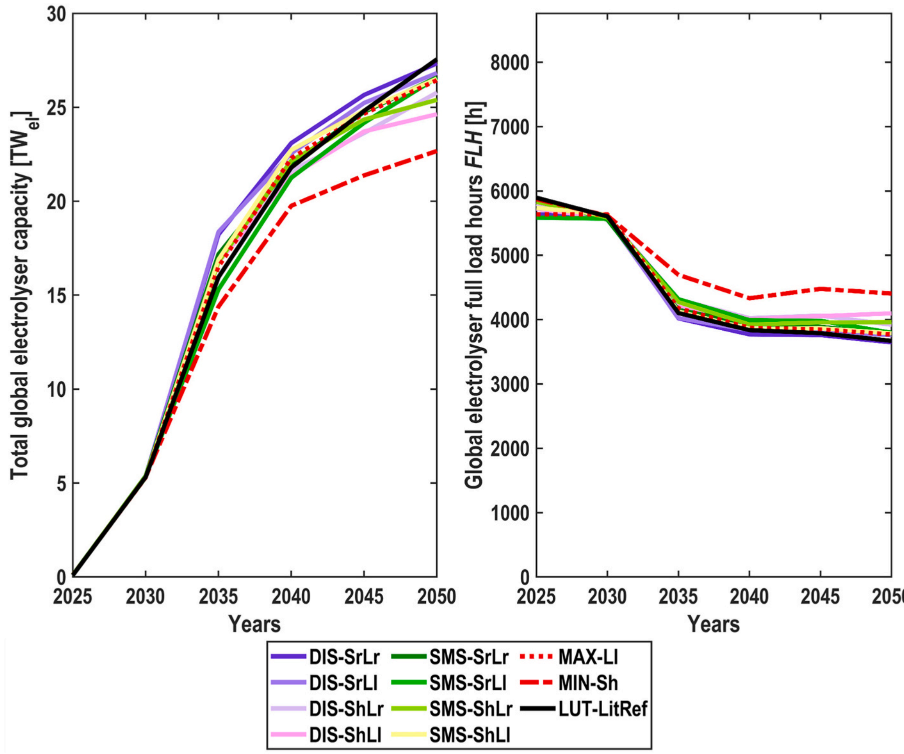

Fig. 10. Cumulative installed electrolyser capacities (left) and electrolyser FLH (right) among all scenarios from 2025 until 2050.

scenarios to ca. 3650 (DIS-SrLr) up to 4100 (DIS-ShLl). These results indicate that electrolysers do not adapt significantly to changed circumstances with higher battery capacities, as a higher baseload operation of electrolysers would result in significantly lower capacities and higher FLH. Therefore, the adaption of the systems has to happen in the hydrogen-to-X processes. Fig. 11 shows the cumulative installed capacity of several relevant synthesis units.

As it can be seen, the synthesis units, DAC, and H_2 energy storage capacities are more sensitive to the battery capex scenarios. One scenario, DIS-SrLr hereby clearly stands out as the most influential scenario with the least synthesis capacities and highest H_2 energy storage capacity. DAC capacities are 9.8 $GtCO_2$/a for DIS-SrLr and between 10.3 $GtCO_2$/a (SMS-SrLr) and 11.6 $GtCO_2$/a, is a decrease of up to 15.5% for the DIS-SrLr. Methanation capacities are as low as 0.9 $TW_{CH4,LHV,out}$ for DIS-SrLr and within a range of 1.2 $TW_{CH4,LHV,out}$ and 1.7 $TW_{CH4,LHV,out}$ (SMS-SrLl). Fischer-Tropsch liquids (FTL) production capacities do not differ significantly, which is due to their minimum load requirement of 50%, restricting larger operational changes. Capacities are in a range of 2.2 $TW_{FTLLHV,out}$ for all new scenarios and slightly higher at 2.3 $TW_{FTL,LHV,out}$ for the LUT-LitRef scenario, by 2050. Methanol (MeOH) synthesis units can be used flexibly, therefore, their installed capacity varies strongly between 2.6 $TW_{MeOH,LHV,out}$ for DIS-SrLr as an extreme case and between 2.9 $TW_{MeOH,LHV,out}$ (MIN-Sh) and 3.5 $TW_{MeOH,LHV,out}$ (LUT-LitRef). For DIS-SrLr, a decrease of ca. 25.7% in methanol synthesis units can be achieved. Ammonia (NH_3) synthesis units do not differ as much, though DIS-SrLr stands out in 2040 and 2045 with the lowest capacities installed, though catching up with other scenarios in the last time step. The capacities for ammonia synthesis lie around 0.4–0.5 $TW_{NH3,LHV,out}$ for all scenarios. Even though being a flexible option, ammonia synthesis does not rely on CO_2 as feedstock and, therefore, seems not to be coupled to DAC as other synthesis units do. All synthesis processes, however, use H_2 as feedstock. H_2 energy storage plays a leading role in the shift of synthesis units' operation. The capacity for H_2 energy storage differ significantly between 44.6 $TWh_{H2,LHV,cap}$ (MIN-Sh) and 65.7 $TWh_{H2,LHV,cap}$ (SMS-SrLr) with DIS-SrLr being the outlier at 79.7 $TWh_{H2,LHV,cap}$, with a cumulative H_2 energy storage capacity 39% higher than the LUT-LitRef scenario and 79% higher than the minimum value among the scenarios.

The impact of the battery capex scenarios on the general shift in operational procedure of synthesis units and scaling of H_2 energy storage can be explained as following: As no significant additional solar PV capacity is installed, and electrolyser capacities differ only minorly, the electrolysers flexibly work as without capex variation as explained above. Synthesis unit capacities, however, can be lowered and operated less flexibly, which is possible with low-cost and efficient additional battery capacities. The reduced electricity load during the day gives more chance to batteries being charged during the day and power the synthesis units during the night. Electrolysers, instead of directly delivering H_2 to the synthesis units, charge the H_2 energy storage, which explains the sensitiveness of the H_2 energy storage to the capex scenarios.

3.3.3. Economic impact

The impact of battery capex scenarios on the overall system economics is depicted in Fig. 12, showing the annualised system cost of the full energy-industry system, the levelised cost of electricity (LCOE) consisting of electricity generation, cost of storage, curtailment, and fuel. The levelised cost of final energy and non-energy use (LCOFE) express the cost per final energy unit and is calculated by dividing the annualised system cost by the total final energy and non-energy use demand.

For all three parameters, the results among the scenarios do not differ significantly. This result means that on the one hand, the installations of battery and H_2 energy storage capacities are varied, and the operation strategy of synthesis units is adapted, but on the other hand, it indicates that the final cost improvement is rather small. This effect means that improvements for one technology bring additional cost for another technology, and in sum all scenarios result in a similar cost optimum. The total annualised system cost first increase from ca. 8935 b€ in 2025 to a range between 12,085 b€ (DIS-SrLr) and 12,412 b€ (LUT-LitRef),

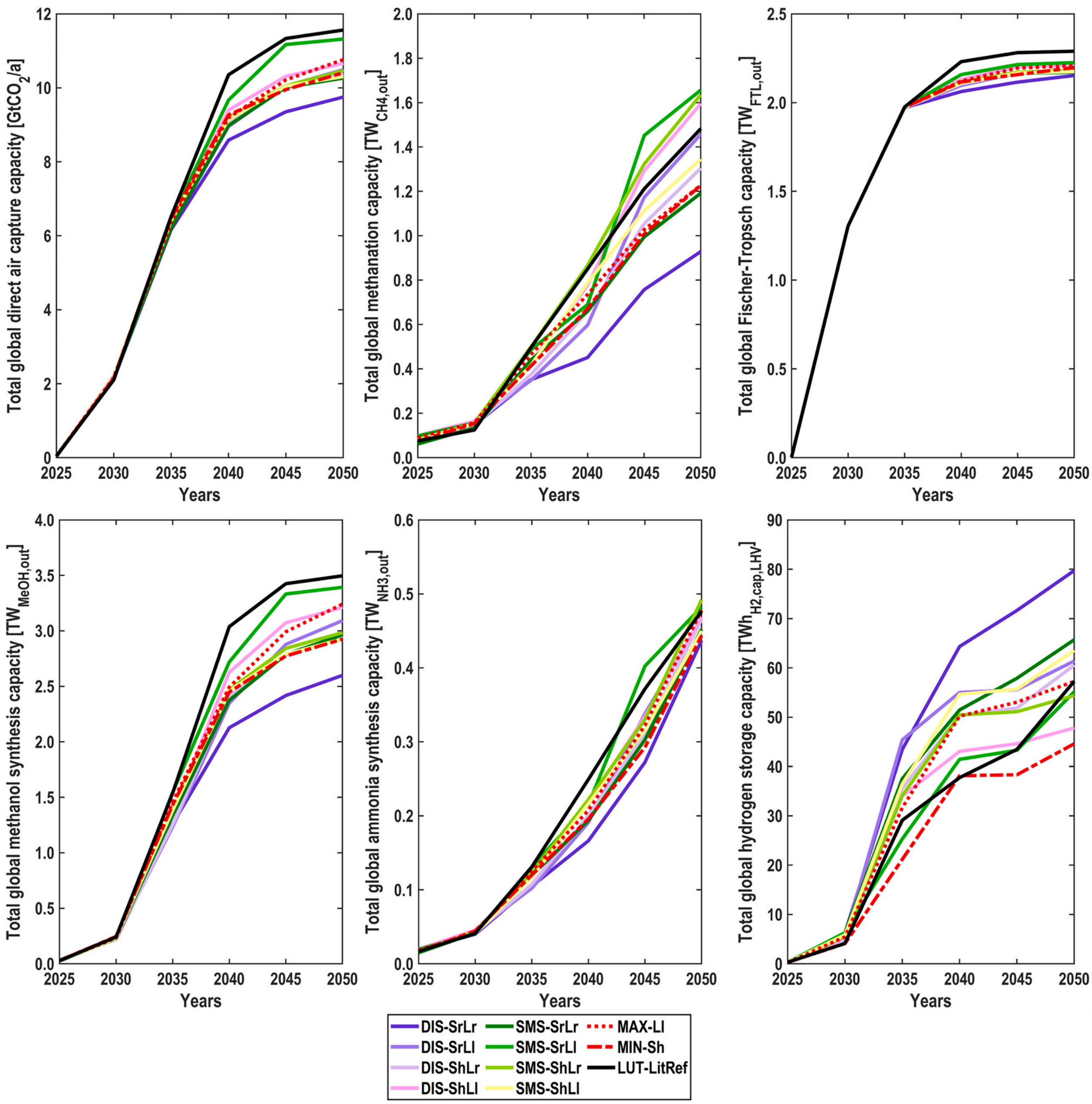

Fig. 11. Cumulative capacities of DAC (top left), methanation (top centre), Fischer-Tropsch (top right), methanol synthesis (bottom left), ammonia synthesis (bottom centre), and H_2 energy storage (bottom right) units among all scenarios from 2025 until 2050.

and then decrease to a range between 10,177 b€ (DIS-SrLr) and 10,866 b€ (LUT-LitRef) in 2050. From about 83.5 €/MWh$_{el}$ in 2025, the LCOE drops to 39.5 €/MWh$_{el}$ (DIS-SrLr) up to 44.1 €/MWh$_{el}$ (LUT-LitRef) in 2040, then continue at a smaller reduction rate to ca. 36.1 €/MWh$_{el}$ (DIS-SrLr) to 38.7 €/MWh$_{el}$ (LUT-LitRef) in 2050. The LCOFE first increase from ca. 65.0 €/MWh in 2025 to about 80.0 €/MWh in 2030, which is caused by a more strongly increasing total annualised system cost than the final energy demand increase, compared to electrification and cost reductions slowing down the total annualised system cost increase after the second time step. Therefore, after 2030 the LCOFE also fall, though less significantly than LCOE to 55.5 €/MWh (DIS-SrLr) up to 59.2 €/MWh (LUT-LitRef) in 2050. As the impact of the capex scenarios is not clearly visible, Fig. 13 shows the utility-scale battery installation rates over the LCOE and LCOFE achieved in the respective time step.

By means of this visualisation, several insights on the transition dynamics of the different capex scenarios can be obtained. The first two time steps (until 2025 and 2025–2030) are insignificantly important to the battery installations. In the second time step (2025–2030), some batteries are already installed; however, for all new scenarios, the added capacity is around 3.3–3.4 TWh$_{cap}$. The most crucial time step is the 2030–2035 time step, which is specifically marked in Fig. 13. Throughout all scenarios, the achieved LCOE in this time step lies in a relatively narrow range of 52.3–54.9 €/MWh$_{el}$ and the LCOFE between 74.7 and 76.9 €/MWh. The cost optimisation, therefore, tries to push the LCOE below 55.0 €/MWh$_{el}$ to achieve LCOFE below 77 €/MWh in this time step. As electrification becomes more important and the availability of low-cost electricity is of upmost importance, while batteries as a core component of the future electrified energy-industry system also play a major role, battery capacity installations are adapted to the situation. It can be clearly noticed that the MIN-Sh scenario especially

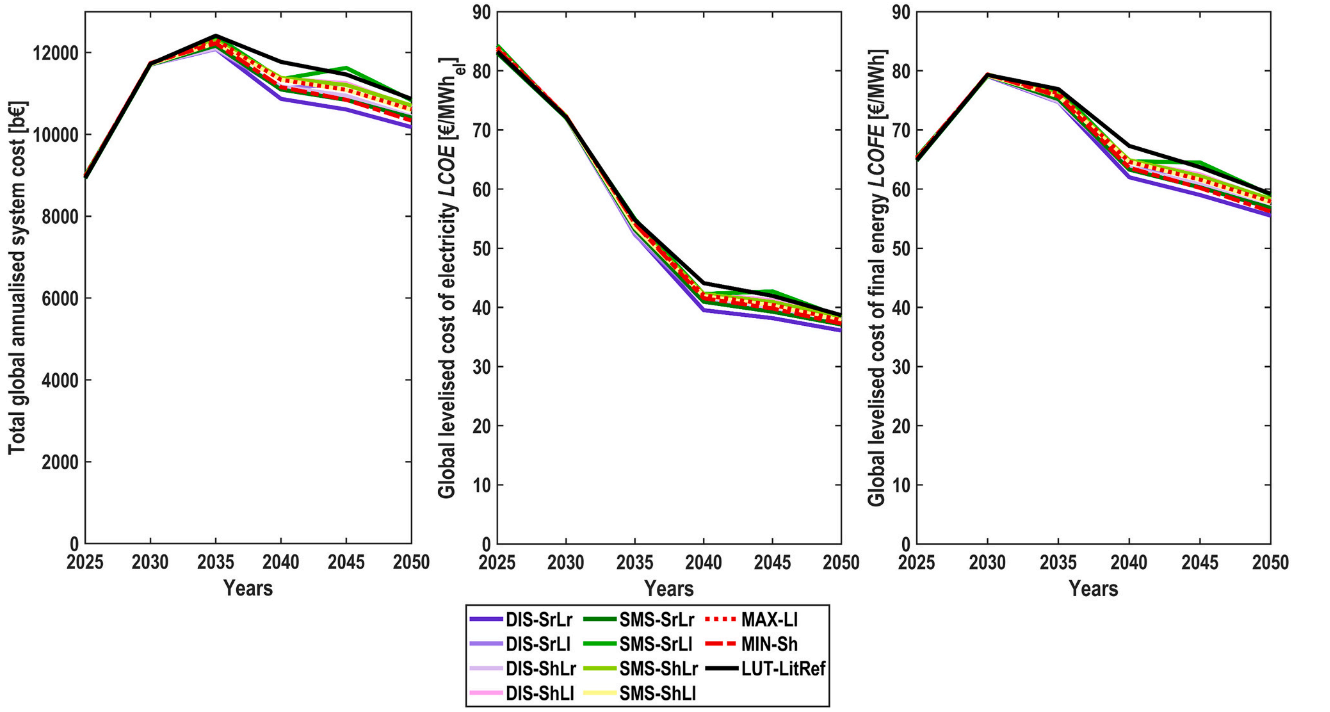

Fig. 12. Total annualised system cost of the entire energy-industry system (left), LCOE (centre), and LCOFE (right) among all scenarios from 2025 until 2050.

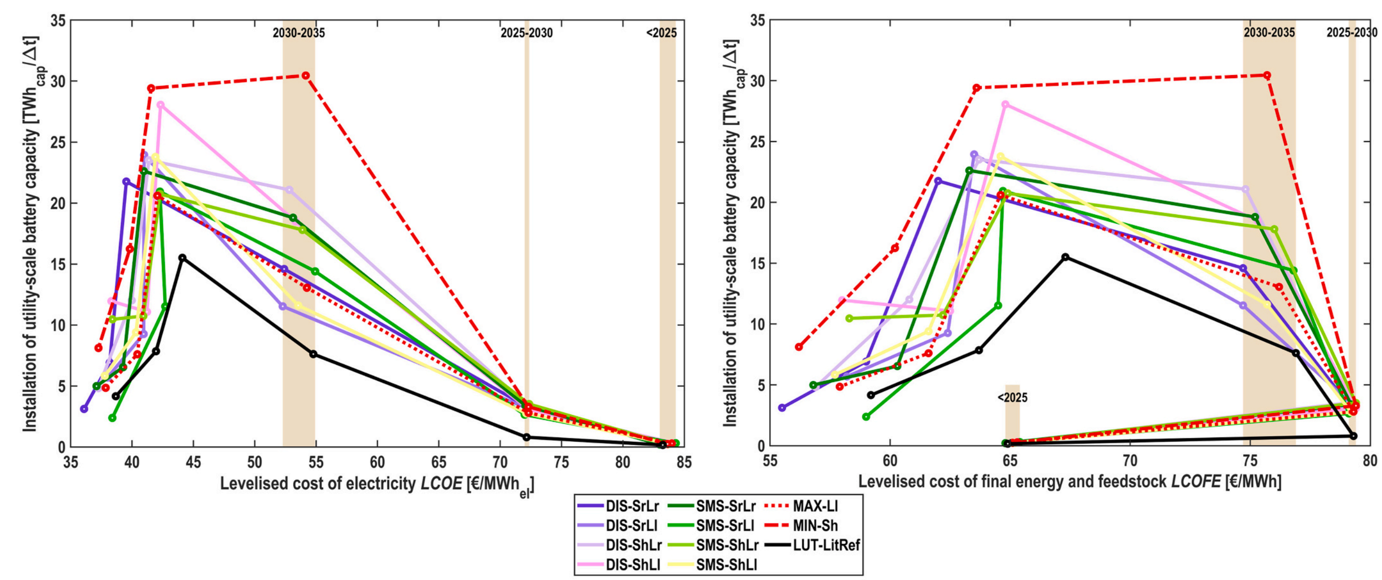

Fig. 13. Installations of utility-scale battery capacities over LCOE (left) and LCOFE (right) achieved in the respective time step. Additionally marked are the installation time frames before 2025, 2025–2030, and of the crucial 2030–2035 time step.

makes use of cheap batteries and goes for an extreme push in battery capacities at this point by installing more than 30 TWh_{cap}. All other scenarios react more moderately, which is a consequence of the relatively high capex difference of the MIN-Sh scenario in the early years of the transition.

The energy system is very sensitive to small capex changes for utility-scale batteries. Therefore, even though the capex for the DIS-SrLl and SMS-ShLl is lower than for the MAX-Ll scenario, less batteries are installed in this time step. However, this time step is the most crucial as all battery capacity installed stays in the system until or rather beyond 2050, as the lifetime of 20 years is assumed to be fully used for the technology. Therefore, if the optimisation went for high battery additions in this time step, it blocks newer battery capacities in later time steps that would be able to achieve slightly lower time cost or LCOE. This effect can be clearly seen for three different groups: MIN-Sh, DIS-ShLr, SMS-SrLr, and SMS-ShLr scenarios install a relatively high capacity of batteries in the 2030–2035 time steps, while in the following time step the installation rate only increases slightly or is even reduced. The second group of scenarios, DIS-SrLr, DIS-ShLr, SMS-SrLr, and MAX-Ll, installs a moderate amount of batteries in this time step and are able to almost linearly increase the battery capacity additions in the next time steps. The DIS-SrLr seems to have the most favourable legacy system, as in the following time steps it is in the lead with the lowest LCOE and LCOFE. The DIS-ShLl is a special case as the capex decrease is relatively slow, and between 2035 and 2045 experience a significant drop, leading to a relatively high installation rate in both 2030–2035 and 2035–2040 time steps. The third scenario group consists of the SMS-ShLl, DIS-ShLr, and LUT-LitRef, with the lowest installation rates in 2030–2035, but with a clear uptake of battery capacity installations in the next time step. The reason for this trajectory lies in the development of the battery capex, as the LCOE finally follow the cost reduction trajectory of utility-scale batteries. Scenarios with a high relative cost reduction in the first time steps tend to install more batteries early on, while in scenarios with moderate cost reductions less batteries are installed, leaving room for a slightly more cost-optimised system later on without the burden of a more costly legacy system. The difference, however, is almost negligible if the overall energy system is optimised.

4. Discussion

In this section, similarities and respective co-benefits of SIB and LIB productions is discussed in Section 4.1, the dependency of the global energy-industry system on LIBs and the role of SIBs in ending the discussion on availability of short-term storage is discussed in Section 4.2. Section 4.3 discusses the limitation of this study.

4.1. Sodium-ion battery as drop-in technology

Although SIBs and LIBs are made from different materials, their production processes are very similar, meaning that SIBs can be considered a “drop-in” technology that can fit into existing production systems with ease [50,108], adapting specific processes for manufacturing optimisation [108]. This close similarity makes it easier to switch to producing SIBs without causing disruptions or requiring complex adjustments, which could make the transition to this new technology more efficient and straightforward.

While still slightly more expensive than LIB today, SIB are found to achieve cost parity in the very short future, and to become cheaper than competing LIB on the medium term. This cost reduction is driven only by performance progress on material level, as predicted by Batteries Europe key performance indicators [65], holding all other factors fixed. Thus, potential future price increases for individual raw materials are not considered in this estimation due to the impossibility to predict raw material price trends. However, when looking at historic prices, the highest fluctuations can be observed for the more critical materials, including Li and graphite [110,111]. Here, SIB can be expected to have further advantages, with sodium carbonate being a worldwide produced bulk commodity relying on an abundant raw material and corresponding low price fluctuations. Also, hard carbons, required as anode active material, can be produced from a variety of raw materials, among them lignocellulosic biomass, which is ubiquitously available and little prone to supply chain disruptions. These aspects are not considered explicitly in the bottom-up cost model, however advocate for an optimistic assumption regarding the SIB learning curve. In this sense, SIB constitute a potentially more economic additional technology option that can take over part of the demand and even readily jump in and be scaled up in case of unforeseen price increases of LIB.

Learning on cell level is influenced by many factors besides energy density such as economies of scale, process yield improvements, and material prices. The economies of scales are indirectly considered in this study with the assumed manufacturing plant size. High process yields are assumed to be already achieved due to the similarity of SIB production with LIB production. Material price assumptions would be speculative and are covered in different market shares for the capex estimation.

4.2. Energy system dependency on lithium-ion batteries and decoupling via sodium-ion batteries

Battery energy storage is set to play a major role in future 100% RE systems as grid-scale (utility-scale) energy storage [5,112], small-scale energy storage for solar PV prosumers [113], or EVs [114]. Wali et al. [115] mention that battery energy storage integration in RE systems pushed the developments in RE, while highly efficient and low-cost batteries are most certainly the success factor for EVs. As currently the dominating cell chemistry is Li, the current expansion of 100% RE systems globally depends on LIB. A common point of concern or criticism is the availability of Li to supply the large needs for this mineral in the forthcoming exponential growth of stationary batteries and EVs worldwide, which, assuming a well-established recycling system and other factors, seems to be manageable [12]. SIB are able to end this discussion. As shown in this study, the production cost of SIB is already at the same level as LIBs and innovation is gaining more and more momentum. There are three possible scenarios for the development of cell chemistries of battery storage: (i) LIBs preserve its status as dominant technology, and respective recycling efforts do not lead to bottlenecks in Li and natural graphite supply. The battery supply is not at risk. (ii) Li supply in on the edge, while LIBs still remain a major part of the technology mix, SIB can develop at the same rate with the same production efforts, expressed in this study by the shared market scenarios. The supply for batteries is not at risk due to a viable alternative or rather co-existence of at least two viable technologies. (iii) Li and natural graphite supply becomes more critical, leading to low growth rates for LIBs, requiring an alternative technology. This role can be filled by SIBs beyond any doubt, as the resource availability for Na is out of question. Also, future developments such as solid-state batteries are expected to advance energy density. Even though several technical hurdles still need to be overcome, the development is expected for LIB and SIB and thus will not change the price difference substantially. In addition, on short and medium term, solid state batteries are expected to rather serve high performance applications where very high energy densities are required (such as airborne), and less stationary applications with a stronger focus on costs [116].

This study presents a valuable estimation of global total battery energy storage capacity until 2050. The expected 67.9–106.5 TWh_{cap} stationary battery storage capacity is up to 54.5% higher than the expected upper estimation of 68.9 TWh_{cap} by Jacobson [117], and are up to 43.9% higher than the expected 74.0 TWh_{cap} by Bogdanov et al. [5]. Both studies are fully integrated energy systems, which are rare on a global basis. While there is a plenty of literature on raw material bottlenecks for significantly increasing share of EVs, a global estimation of the battery capacity required is not available. Therefore, the 273.7 TWh_{cap} battery capacity for mobile applications estimated in Section 2.2.2 can be seen as a first glimpse in what orders the capacity may lie around 2050.

Currently, LIBs are dominant in the stationary battery market. Since gravimetric energy density is less relevant, SIBs have good chances to take over this market at lower cost. As Chayambuka et al. [118] elaborated in 2020, SIBs seem to have entered the stage of commercialisation, which now a few years later and some battery giants going for market roll-out, seems to have proven right [119,120]. Even mobile applications may be covered by SIBs, where LIBs had the lead due to higher gravimetric energy density [119]. A favourable development for energy density will be as important as a favourable cost development for SIBs to tackle LIBs even on mobile applications.

Possible lock-ins due to established supply lines for Li-based technologies might hinder the uptake of SIBs; however, if the supply of Li is at risk, battery manufacturers can be expected to easily switch their production lines to Na-based technologies as the mature manufacturing processes of LIBs can be also used for SIBs [121]. Given these circumstances, the energy system does remain dependent on battery energy storage technology, however, not on Li-based technology. Critical discussions regarding the affordability of energy storage or the need for a “sunflower society” [122] will become a thing of the past. Technological maturity of SIBs is given, as the idea of large-scale SIBs has been materialised with the first 10 MWh_{cap} SIB storage being in operation in

China as part of a 100 MWh_{cap} project [123]. The relevance of such battery storage projects can be seen in the real world. As an example, the German outlet of the pv magazine called the total of 226 GW of battery storage connection requests received by the transmission grid operators a "battery tsunami" [124]. Jacobson et al. [125] assigned battery storage in California a critical role in providing a stable highly RE system over a long period in the world's 5th largest economy in 2024.

If local manufacturing capacities for SIBs are supported by respective policies, the anticipated rise of battery capacity could create value-add for local economies. Due to the abundancy of the required raw materials, dependency on leading manufacturing countries can be at least reduced, if not fully omitted. Beyond economic value-add, local production capacities for this key technology would also support local job creation [126] and energy security [127]. SIBs can enable such a shift more easily than LIBs since supply chains are not yet established. Swift action is required, as the race for SIB manufacturing leadership is about to begin if the results of this study are taken into practice [28]. Local mining for sodium should be included in respective mining roadmaps to ensure overall sustainability [128].

For the general system structure and economic viability of a 100% RE system, this study has shown no substantial impact of battery capex. The minor, thus counter-intuitive impact of SIBs on the solar PV capacity indicates that even with the LUT-LitRef battery capex, a threshold has been reached with solar PV as the dominating energy source in this century. Lower battery capex, thus, do not influence this situation significantly. The further optimisation of the energy-industry system, however, shifts to downstream processes in the energy conversion chain, which are the synthesis units. Instead of following the availability of electricity from solar PV via direct consumption, low-cost batteries enable to reduce synthesis capacities while allowing for higher FLHs of these units. The amount of electricity used changes only minorly due to the high efficiency of battery energy storage, while the most electricity-intensive technology is DAC, both via direct electricity demand, and indirectly via heat pumps to provide the process heat. One key feature to enable this is low-cost H_2 storage, as produced H_2 is not anymore directly consumed but balanced via H_2 storage. Lower synthesis units' cost, however, are balanced with higher battery capacities installed. This study is the first to encounter such effects in optimising an already largely optimised energy-industry system.

Independently on the scenario, the total annualised cost, LCOE, and LCOFE were within an insignificant variation band. Most important, however, is the overall optimisation of the entire energy-industry system, as the point in time of battery installations matter over the whole transition period. If batteries are installed at moderate pace, leaving room for further cost improvements in the future instead of 'clogging' the system with a more costly legacy system, synthesis units can be run later at lower capacities with a slight cost advantage. The difference, however, is small, and for each case a respective optimisation of the rest of the system can achieve virtually the same cost optimum. A faster decrease in battery cost might open up the possibility for a faster energy transition.

4.3. Limitations

For the energy system model, different cost projection scenarios are applied, assuming SIBs to be equal or cheaper than competing LIBs. The bottom-up cost assessment confirms the assumption of SIB prices decreasing at faster pace than LIB, in line with recent literature [30]. However, it uses constant prices for the individual raw materials based on average historical values (no future predictions). Thus, different developments in the prices of LIB or SIB specific materials might lead to substantially different scenarios not further considered here, being that raw material prices are typically subject to high fluctuations and future developments are impossible to predict. Also, the foreseen progress in terms of material performance is subject to high uncertainty. While the Batteries Europe KPI can be considered as best estimate in this regard [65], new materials might arise and quickly change the overall landscape. However, even if the conclusion that SIB will become a lower cost alternative to LIB in future proves wrong, it still constitutes a competitive alternative based on alternative raw materials that can drop in whenever LIB prices rise due to supply shortages or any other disruption, thus adding robustness to battery deployment scenarios in energy system modelling. The aspect of material cost influenced by recycling has not been included in this study, however, is an interesting question for cell and battery prices especially after 2050 when recycling will play a major role in a sustainable circular economy [129]. Recycling profitability of SIBs may even surpass LIB recycling, making SIBs more economically interesting in the long term [130].

The cost model is tailored for battery cells, while no detailed cost model for large ESS was applied. The system costs for both the battery interface (power-related components) and the battery system, i.e., battery modules, containers, balance of plant, etc., are estimated as a fixed percentage based on literature. While this is an important limitation, the corresponding shares would not differ significantly between LIB and SIB, and the impact on the final conclusions, therefore, is expected to be small. Also, the same cell layout and production cost parameters are used for both LIB and SIB cells. Since SIB share major properties with LIB in respect to electrochemical principles and cell production, this is considered an appropriate assumption, underpinned by the magnitude of shared patents for both technologies (see Section 1.1). Finally, the cell cost estimation is rather deterministic, based on fixed material costs and predicted values for performance parameters, while disregarding the associated high uncertainty, especially for future values. While a detailed uncertainty analysis and a corresponding stochastic approach to cost projections is out of the scope of the present work, it still captures this uncertainty in a qualitative way by defining different learning rate scenarios.

This study assesses the impact of SIB and general battery market cost scenarios on the energy-industry system with regard to stationary batteries. As shown in Section 2.2.2, more than 75% of battery capacities by 2050 will be mobile applications, mostly battery EVs. These capacities are not considered in a cost-optimised way in LUT-ESTM, as the electrification of road transportation is pre-defined in the scenario assumptions with the transition towards the electrification of transportation largely being policy-driven [131]. Different stakeholders involved with possible vested interests avoid the transition of transportation towards the most efficient and most economic option [132], preventing the implementation of the transport sector fully into the cost optimisation of LUT-ESTM. However, this circumstance does not have an impact on the results of this study as SIBs in the current state of development can already be used in mobile applications such as passenger cars [133]. Battery giant CATL recently announced the first mass-produced SIB for mobile applications [119] with others actively working on it, e.g., BYD with a 30 GWh SIB factory [120]. An uncertainty of this study is the market adoption of battery capacities, as estimated in Section 2.2.2. A deviation from this assumed trajectory will have an impact on the cost development, and therefore, on the techno-economics of the overall energy system. This sensitivity is out of scope for this study but should be addressed in future work.

5. Conclusions

The present work applies a bottom-up cost model for determining expected future price trends between lithium-ion (LIB) and sodium-ion batteries (SIB) and incorporates both storage technologies into a global energy system model. As such, this modelling allows for an assessment of the impact of a possible SIB breakthrough on the global energy transition. Applying key performance targets set by Batteries Europe for both LIB and SIB, ceteris paribus, the SIB can be expected to become cheaper than their LIB counterparts on the medium run, and to be less prone to price spikes in raw materials.

For both technologies, price decreases have been faster than assumed in previous works and the capital expenditures to install large-scale battery storage are no longer critical for the deployment of renewables and the defossilisation of the energy-industry system. Interestingly, the battery prices have little influence on the final cost of electricity and do not affect substantially the projected solar photovoltaics capacity. They do, however, affect the hydrogen storage capacity and the fuels and chemicals synthesis capacities, indicating that cheaper batteries allow for a more continuous operation of synthesis plants with correspondingly lower unused capacities. Given the fact that SIB is a drop-in technology that can readily be produced on existing LIB production lines, it can be concluded that concerns regarding a slowdown or hampering of the energy transition due to increasing LIB prices are not a point of concern. SIB can be expected to take a relevant share of the battery market in future, and increasing LIB prices due to, e.g., future material shortages or supply chain disruptions, would be buffered by simply increasing the share of SIB without major effects on the energy system.

This study argues that electrochemical energy storage is not a limiting factor for the global energy transition anymore, and that concerns about insufficient battery availability are most probably not justified. In consequence, this work projects the possibly highest battery demand published so far ranging between 67.9 and 106.5 TWh_{cap} by 2050, above those found in existing cost-optimised energy-industry system projections. The impact of low-cost battery energy storage on the energy-industry system revealed counter-intuitive results: solar photovoltaics capacities do not increase significantly in comparison to the used reference scenario, still battery capacities increase. These capacities are used to shift electricity from daytime to nighttime to run power-to-X processes in higher load.

This study has several policy implications. Firstly, SIB can play a key role in increasing the resilience of the energy-industry system. If sufficient production capacities are available, SIB can meet the demand for batteries in the event of supply shortages or significant price increases for LIB and vice versa. This is possible because existing LIB production lines can be adapted for SIB, effectively positioning it as a drop-in technology. This requires expertise, investment decisions, and policy support, however, if these are in place, batteries will no longer be a critical element for the green transition. Secondly, battery prices are not a deciding factor in defossilisation. Although cheaper batteries increase the use of power-to-X processes, they have little impact on overall defossilisation and energy prices. The large-scale adoption of SIBs, given the similarities in technology to LIBs and possible shared production lines, as well as similar cost and first pilot projects today, does not seem to be a problem, which means there is no techno-economic barrier for large-scale battery technology adoption. Thirdly, a moderate deployment of batteries is more cost-efficient than an overly rapid deployment. Therefore, careful steering of battery deployment is recommended to avoid such effects. Furthermore, EU countries are advised to support the production of systems that are potentially slightly more expensive, but which are based on abundant materials, in order to maintain or achieve technology sovereignty.

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CRediT authorship contribution statement

Dominik Keiner: Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Friedrich Jasper:** Writing – review & editing, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dmitrii Bogdanov:** Writing – review & editing, Validation, Software, Methodology. **Gabriel Lopez:** Writing – review & editing, Validation, Methodology, Investigation. **Jens Peters:** Writing – review & editing, Visualization, Validation, Software, Resources, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Manuel Baumann:** Writing – review & editing, Validation, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Christian Breyer:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Marcel Weil:** Writing – review & editing, Validation, Resources, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

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Data availability

The battery cell cost model is provided as spreadsheet file in Supplementary material 3.

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