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Are we too pessimistic? Cost projections for solar photovoltaics, wind power, and batteries are over-estimating actual costs globally

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HIGHLIGHTS

- Cost assumptions from 40 studies on 4 supply and 1 storage technology were systematically analysed.
- Recent projections reveal significant cost reductions compared to the older studies.
- Utility-solar PV and battery CAPEX and LCOE projections are overly pessimistic.
- CAPEX spread is driven by outdated data, learning rates, and regional soft costs.
- Many LCOE projections use arbitrary rates, ignoring region-specific costs and risks.

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ABSTRACT

Cost projections of renewable energy technologies are one of the main inputs for calculating energy transitions. Previous studies showed that these projections have been overestimated. In this study, we update the assessment of cost projections, comparing over 40 studies and 150 scenarios, between 2020 and 2050 of the main renewable energy technologies: utility-scale solar photovoltaics, rooftop solar photovoltaics, onshore and offshore wind, and Li-ion batteries. Generally, all studies reviewed expect a strong reduction in the levelised costs and capital expenditures, though with different reduction levels. While the revised cost projections have improved and are more aligned with historical trends, they are still too pessimistic. Most cost projections for 2050 are in the same ballpark as costs already observed today. Notably, the investment costs for utility-scale photovoltaics in the U.S. for 2050 are projected to be 30 % higher than current costs. We also observed a large disparity between cost projections, particularly for solar photovoltaics and offshore wind, where the most optimistic investment cost projections are up to four times lower than the most pessimistic. In the case of levelised costs, this dispersion can somewhat be explained by underlying issues such as arbitrary discount rate assumptions that fail to account for local costs of capital and risks. To sum up, global renewable energy technology costs are decreasing faster than what studies assume, highlighting an ongoing pessimism in cost projections.

1. Introduction

Decarbonising the energy industry through the implementation of sustainable Renewable Electricity (RE) systems is one of the main pillars of the fourth industrial revolution [25]. Renewable power capacity additions reached 88 % of all global power capacity additions in 2022 [11]. The cumulative global installed capacity of RE has risen sharply in recent years from around 1.7 TW in 2014, to 2.5 TW in 2019, and a projected 4.5 TW by the end of 2024. As we build out more RE capacity (economy of scale) and as efficiencies improve (technological progress),

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costs decline (learning curves) [69]. In addition to declining costs of RE systems, incentives, climate goals and carbon prices have also pushed for infrastructure expansion [5,68].

Cost projections of RE technologies are one of the main inputs for energy system modelling tools [20,83]. However, based on the comparisons made between current and previous cost projections, it can be observed that most studies overestimate the cost of RE technologies [51]. Projections overestimate the costs of wind power and solar photovoltaics (PV) by excluding existing flexibility strategies like dispatchable renewables, demand response, and grid expansion, and by adding inflated integration costs due to low spatial and temporal granularity [19]. Many energy models assume that technology costs evolve independently, but in practice, they decline with increased cumulative capacity due to the learning curve effect [101]. Utilising inaccurate learning curves for cost trends in RE technologies have also resulted in the overestimation of costs [19].

Early studies assessing the accuracy of cost projections for RE technologies often focused on limited variations of technologies in a single region. For example, studies examining onshore wind in the United Kingdom [15], and single-axis tracking solar PV, onshore wind, and offshore wind in the United States (U.S.) [7] all found that the cost projections and assumptions available at the time were overestimating actual costs. These cost overestimations can result in inaccurate and less impactful decisions regarding the decarbonisation of the energy systems, as it is highly influenced by projections of the technology costs [23,103]. Beyond these limited case studies, there has been only one study comprehensively examining cost projections at a both global and regional scale [105]. This study systemised about 20 studies published before 2019 on cost projections for selected RE technologies and compared them with the actual costs of RE systems on a global and regional scale. The results overwhelmingly indicated that most available cost projections overestimate the real cost of RE systems.

Despite the contributions of these works, their technological resolution remains low. For instance, in [105], solar PV (the main technologies today as measured by yearly capacity deployed) was lumped into a single category—instead of differentiating between the main types like rooftop and utility-scale. This is particularly important due to the significant differences in the cost components between these two categories. Another limitation of the previously published analyses is that they are now outdated, given the fast pace of RE developments.

In this work, we will address the shortcomings by providing an updated cost analysis for the main RE technologies, including solar PV at utility and rooftop scale, wind on and offshore, as well as the widely commercialised Li-ion batteries. We will look at Levelised Cost of Electricity (LCOE) and Capital Expenditure (CAPEX) projections for different integration scenarios across the globe from the most recent publications and reports and compare them with observed real market data. Concretely, our contributions are:

- To compile an up-to-date database of cost projections of the main RE technologies;
- To measure how the cost projections differ from or agree with each other;
- To detect possible changes in trends when compared to previous studies;
- And to compare the cost projections to currently observed costs in markets.

In total, this study systematises and analyses the cost assumptions of the main RE technologies from 40 studies across diverse geographical regions and over 150 scenarios, for 4 electricity supply and one major storage technologies. To our knowledge, this would make it the most comprehensive and updated analysis of the RE technologies' cost projections.

The upcoming section contains the methodology and a list of reports and studies used for the cost comparison. The third section is dedicated to the results of the analysis of the LCOE and CAPEX projections. Then we will discuss the results in Section 4, and our conclusions will follow in Section 5.

2. Methods

This work will systemise and analyse cost projections for RE technologies from leading publications and compare them to real costs. This work focuses on the most common RE technologies, which are utility-scale PV, rooftop PV, onshore and offshore wind, and Li-ion batteries.

The next subsection will elaborate on the reasons why we chose CAPEX and LCOE for our analysis, as well as on the selection process of the considered publications. Subsection 2.2 will provide insights into the challenges we faced when systematising the data and the resulting assumptions we made.

2.1. Analysed indicators

Energy system models present the economic results using two main indicators – CAPEX and LCOE. There are advantages and disadvantages associated with each of these indicators.

CAPEX is an indicator of the total investment cost for an energy technology. The CAPEX generally includes equipment and infrastructure costs (e.g., battery pack, container, thermal protection systems, civil structure, etc.), installation costs (e.g., engineering, startup, and commissioning), and electrical infrastructure and interconnection costs (e.g., cabling, inverters, transformers, management systems, etc.) [102]. Although a higher capital requirement is one of the main challenges of RE integration compared to that of conventional generation like fossil fuel power plants, the required capital for installation of RE plants has reduced remarkably due to technology improvements and public incentivisation in recent years [35,106]. CAPEX consists of a higher portion of financial planning for RE, and therefore, is a significant cost factor as it is not constrained to regional volatility and is computationally convenient for comparisons as it needs fewer assumptions.

LCOE is a cost indicator that is calculated based on performance-, investment-, operation-, and uncertainty-related costs [88]. LCOE is calculated by dividing lifetime costs (CAPEX, operation, and maintenance) by the lifetime electricity produced for each technology in a specific region. This metric, although more complex, provides comprehensive and clear economic outputs that are suitable for decision-making in grid expansion [22]. However, the dependence on regional and local criteria in the calculation such as discount rates unique to each country, access to RE sources and markets, accessibility to cost-effective RE technologies, neglecting system integration costs, and other possible endogenous cost factors can lead to low-quality comparisons of this index between countries.

2.2. Selection process and sources

We selected reports and journal publications that focused on RE cost projections, based on the following criteria:

- **Long-term energy scenarios:** including at least one long-term energy scenario. This scenario should include plans for the mix of energy sources.
- **Cost indicators:** including two key cost indicators – CAPEX and LCOE.
- **Publication date:** released from the year 2020 onwards to effectively provide an update respective to Xiao 2021.
- **Spatial focus:** focusing on the international and/or national scale of energy system scenarios, trying to cover the U.S., Europe, and countries in Asia and Africa.
- **RE technology costs:** considering the costs of RE technology. Specifically, these costs should be reported for projects within the same range of generation/storage capacity.

Projections were selected based on the abovementioned criteria from the available academic, state-owned, or non-governmental databases and repositories and are listed in Table 1. The inflation is handled by normalising the costs to the value of the U.S. dollar in the year 2023.

This resulted in 40 studies across diverse geographical regions and over 150 scenarios. These scenarios refer to conservative, moderate, and advanced insights on the development of RE technologies. Scenarios categorised as "conservative" reflect cases where the estimations have the lowest reduction rate for the future. This is somewhat similar to a case we might call "business-as-usual". In these scenarios, cost projection models are not predicting large reductions in future costs due to limited technological advances, limited incentivising regulations, and/or limited uptake of technology utilisation. Conversely, "Advanced" scenarios are the most optimistic. These scenarios are expecting advancements in technology efficiency, supporting regulations, and higher uptake rates for technology implementation. "Moderate" scenarios are somewhere in between, reflecting a moderate level of improvement in the aforementioned parameters.

The LCOE and CAPEX projections are extracted from the studies in Table 1 until the year 2050 due to the common choice of 2050 as the final year in most RE transition scenarios. We compared our data with historical global market values from the International Renewable Energy Agency [50] for utility-scale solar PV, as well as onshore and offshore wind power. IRENA collects cost information from large energy projects around the world to estimate price ranges. They also use a weighted average to report the typical global costs for two key indicators: LCOE and CAPEX. For rooftop solar, we used data from Lazard [56–64] where residential systems are assumed to be 0.005 MW and commercial/industrial systems are 1-5 MW. For battery storage, we used data from BloombergNEF [10], which covers systems with capacities ranging from 0.5 MW to several megawatts. LCOE trends are compared with the real LCOE and auction values in the market, and the CAPEX trends are compared with the total investment values for each RE technology. The cost data for PV, and wind technologies used in this study are available online [50]. All the extracted data in this study is converted to USD and adjusted for inflation to the year 2021.

2.3. Challenges and assumptions

We aimed to have a cost projection for all technologies in each of the world regions. As not all studies provided cost projections for all technologies, we resorted to using multiple reports for a given region. For instance, Sens et al. [86] includes the European costs for onshore wind, offshore wind, and utility-scale PV but excludes rooftop PV. For that reason, we included studies such as ([13,32] for the rooftop PV technologies in Europe.

There are around 20 national-scale reports used in this study that consider the cost indicators' trends for the USA, United Kingdom, China, European Union, India, Germany, Brazil, Australia, Egypt, Iran, Japan, Turkey, Singapore, and Thailand, while the others will discuss internationally.

To create a thorough cost review, we made simplifications where reports lacked clear cost data. This included averaging RE cost indicators when only the lowest and highest ranges were given and assuming "PV" plants were utility-scale.

2.4. Data availability

The resulting database is available on [98]. In short, it comprises the CAPEX and LCOE projections mentioned in Table 1. Each sheet shows a given technology from our paper.

3. Results

In this section, we will first analyse the investment costs of the selected RE technologies (utility PV, rooftop PV, onshore wind, offshore wind, Li-ion batteries) in section 3.1, followed by the levelised costs of electricity in section 3.2. In each section, we will compare the cost projections from the diverse studies that we have compiled between each other and to observed market costs.

For each technology and economic indicator, we will use similarly structured plots, like Fig. 1. Their x-axis shows the scenario year and the y-axis the cost ranges. In the case of CAPEX, this is the cost per installed capacity (US $/kW), and in the case of LCOE, this is the cost per energy generated (US $/MWh). Each plot shows several cost projections from the studies we included in the present work. Each study might have several scenarios, indicated in the shaded areas, generally categorised as conservative, moderate, and ambitious emission targets. These cost projections are compared to historic costs, plotted in black.

3.1. Investment costs

3.1.1. Utility-scale solar PV

According to Fig. 1, the solid black line with grey shading representing actual average CAPEX with ranges has a sharp decline in the global average required investment for solar PV plants, with an average of 500 $/kW by the end of 2023 (Fig. 1). Compared to the referenced reports projected costs, the actual CAPEX is lower than the projected costs for almost all of the reports for the same year. In comparing future projections to known costs today, we found that the average assumed projection for 2030 indicates a cost range of 350-1050 $/kW, where recent data on required investment for utility-scale PV plant installations in regions like Germany [86] and India [47] demonstrate that their CAPEX falls below or within this range. If this reducing trend in actual CAPEX data continues, in upcoming years actual CAPEX values could be lower than projections for 2050. This is a clear indication that the cost projections do not reflect the recorded falling trend in the actual CAPEX. The average cost projections for utility-scale PV in 2050 could range from 160 to 630 $/kW according to the projections, diverging by a factor of around 4.

In the short term, Egypt has the highest projected cost, estimated at around $1600 per kW for 2025 [37]. On the contrary, [96] presents the lowest projected costs from a global perspective among the studies for the same year. Overall, most of the studied reports project an exponentially damping trend for CAPEX, suggesting that their assumptions do not account for significant decreases beyond 2030.

3.1.2. Rooftop PV

Market investment costs for rooftop PV technology are showing a decreasing trend from 2015 onwards. Until the beginning of the year 2023, it is observed that the actual CAPEX of this technology has decreased to 883 $/kW on average (Fig. 2). Limited predictions currently exist for the average investment cost of rooftop solar PV in 2030, with estimates varying from 530 to 1010 $/kW on average. The trendlines do not indicate a significant breakdown in investment costs for rooftop PV systems beyond 2035. For instance, projections for Singapore suggest that the cost trend will stabilise after 2034, maintaining at approximately 560 $/kW. Looking ahead to 2050 and opting out the outliers, global forecasts for investment costs in rooftop PV range from 330 to 685 $/kW, diverging by a factor of approximately 2.

The projections from [52,67] remain as upper and lower outliers, respectively. Historical data from 2015 reveals a notable trend wherein the investment cost per kW for rooftop PV plants decreased at a faster pace than all projected trendlines. This observation indicates the potential for rooftop PV's CAPEX to dip even below the lowest projections in upcoming years if the observed rate of reduction persists.

3.1.3. Onshore wind

For onshore wind technology, the current cost range is between 770 and 2100 $/kW (Fig. 3). Cost projections for the year 2030 is expected to be around 940-1660 $/kW, showing a narrower range compared to the current costs for onshore wind. Comparing projections to the actual

Table 1
Analysed academic papers and public reports in this study.

Reference	Type*	Title	Geographical scope	Published year	Considered technologies: CAPEX Utility-scale PV	CAPEX Rooftop PV	CAPEX Onshore wind	CAPEX Offshore wind	CAPEX Li-Ion Battery	LCOE Utility-scale PV	LCOE Rooftop PV	LCOE Onshore wind	LCOE Offshore wind
[77]	R	2023 Annual Technology Baseline (ATB) Cost and Performance Data for Electricity Generation	U.S.	2023	✓	✓	✓	✓	✓	✓	✓	✓	✓
[48]	R	World Energy Outlook 2023	Europe, China, India	2023	✓		✓	✓		✓		✓	
[14]	J	Energy transition for Japan: Pathways towards a 100 % renewable energy system in 2050	Japan	2023	✓	✓	✓	✓	✓				
[70]	R	Levelized cost estimates of solar photovoltaic electricity in the United Kingdom until 2035	United Kingdom	2023						✓	✓		
[74]	J	The potential role of a hydrogen network in Europe	Europe	2023	✓	✓	✓	✓	✓				
[18]	J	Reflecting the energy transition from a European perspective and in the global context—Relevance of solar photovoltaics benchmarking two ambitious scenarios	Europe	2023	✓	✓	✓	✓	✓				
[86]	J	Capital expenditure and levelized cost of electricity of photovoltaic plants and wind turbines – Development by 2050	Germany	2022	✓		✓	✓		✓		✓	✓
[49]	J	Assessment and determination of 2030 onshore wind and solar PV energy targets of Türkiye considering several investment and cost scenarios	Türkiye	2022	✓		✓						
[55]	R	Levelized Cost of Electricity- Renewable Energy Technologies (Fraunhofer ISE)	Germany	2021						✓	✓		
[37]	R	Accelerated growth of renewables and gas power can rapidly change the trajectory on climate change	Egypt, Brazil	2021	✓					✓		✓	
[84]	R	Proyecciones de costos inversión y LCOE	Chile	2021	✓					✓			
[67]	J	Combined solar power and storage as cost-competitive and grid-compatible supply for China's future carbon-neutral electricity system	China	2021		✓					✓		
[40]	R	GenCost 2020-21 – Consultation draft	Australia	2021		✓							
[72]	R	Plano Nacional de Energia 2050	Brazil	2020	✓		✓	✓					
[38]	J	Assessment of a cost-optimal power system fully based on renewable energy for Iran by 2050 – Achieving zero greenhouse gas emissions and overcoming the water crisis	Iran	2020	✓	✓	✓		✓	✓			✓
[32]	R	Fact sheets about photovoltaics	Europe	2020		✓					✓		
[87]	R	Update of the Solar PV Roadmap for Singapore	Singapore	2020		✓					✓		
[21]	J	Customer economics of residential PV–battery systems in Thailand	Thailand	2020							✓		
[73]	J	An evaluation of energy storage cost and performance characteristics	U.S.	2020					✓				
[43]	J	Greenhouse gas consequences of the China dual credit policy	China	2020					✓				
[97]	J	Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity	Europe	2020	✓				✓				
[28]	R	Estimating the Cost of Grid-Scale Lithium-Ion Battery Storage in India Energy Technologies Area Lawrence Berkeley National Laboratory	India	2020					✓				
[29]	R	Energy Transition Outlook 2023: A global and regional forecast to 2050	World	2023						✓		✓	
[1]	J	Accelerating the Renewable Energy Revolution to Get Back to the Holocene	World	2023					✓	✓		✓	

(*continued on next page*)

Table 1 (*continued*)

Reference	Type*	Title	Geographical scope	Published year	Considered technologies								
					CAPEX					LCOE			
					Utility-scale PV	Rooftop PV	Onshore wind	Offshore wind	Li-Ion Battery	Utility-scale PV	Rooftop PV	Onshore wind	Offshore wind
[10]	R	Lithium-Ion Battery Pack Prices Hit Record Low of $139/ kWh	World	2023					✓				
[39]	R	Battery market forecast to 2030: Pricing, capacity, and supply and demand	World	2022					✓				
[94]	R	Financial Incentives for Hydrogen and Fuel Cell Projects	World	2022				✓					
[52]	J	Low-cost solutions to global warming, air pollution, and energy insecurity for 145 countries	World	2022	✓	✓	✓	✓		✓	✓	✓	✓
[92]	J	It Is Still Possible to Achieve the Paris Climate Agreement: Regional, Sectoral, and Land-Use Pathways	World	2021	✓	✓	✓	✓					
[41]	J	Cost reductions in renewables can substantially erode the value of carbon capture and storage in mitigation pathways	World	2021	✓		✓	✓					
[13]	J	Full energy sector transition towards 100 % renewable energy supply: Integrating power, heat, transport and industry sectors including desalination	World	2021	✓	✓	✓	✓	✓				
[17]	J	Estimating long-term global supply costs for low-carbon hydrogen	World	2021			✓						
[104]	J	Expert elicitation survey predicts 37 % to 49 % declines in wind energy costs by [72]	World	2021								✓	
[9]	R	New Energy Outlook 2021	World	2021									✓
[71]	J	Battery cost forecasting: A review of methods and results with an outlook to 2050	World	2021					✓				
[46]	R	Levelized Cost of Electricity Calculator	World	2020					✓				
[31]	R	Battery Energy Storage Lifecycle Cost Assessment Summary	World	2020					✓				
[6]	J	Projecting the Competition between Energy-Storage Technologies in the Electricity Sector	World	2020					✓				
[81]	J	Projecting the price of lithium-ion NMC battery packs using a multifactor learning curve model	World	2020					✓				
[16]	R	BP Energy Outlook: 2022 edition	World	2020						✓			✓

* R: Reports, white papers, and state/corporate documents, J: Journal papers and academic studies.

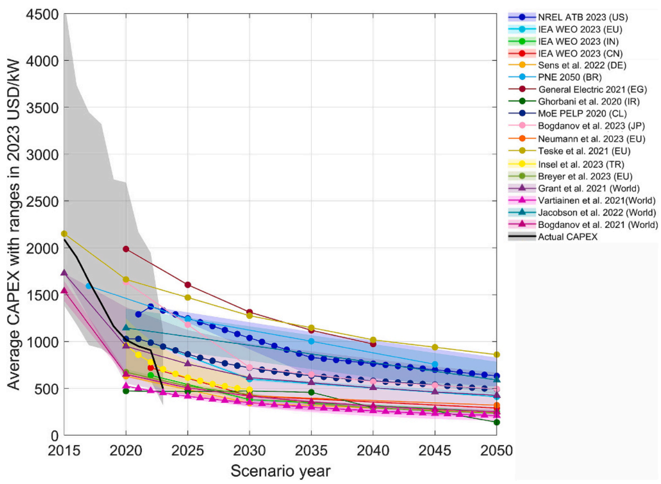

Fig. 1. Utility-scale PV CAPEX projection trendlines and ranges compared to the actual cost trend and range (solid black line with no markers, and grey shaded area)

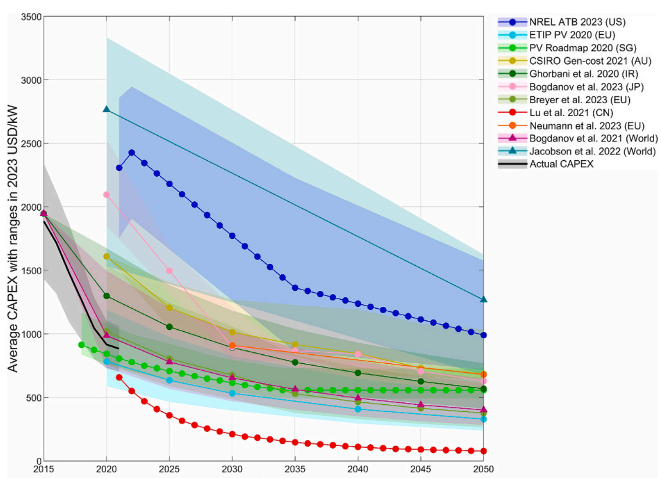

Fig. 2. Rooftop PV CAPEX projection trendlines and ranges compared to the actual cost trend and range (solid black line with no markers, and grey shaded area)

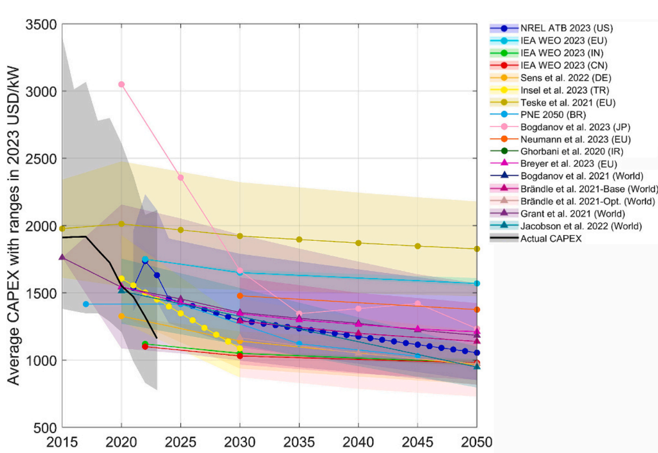

Fig. 3. Onshore wind CAPEX projection trendlines and ranges compared to the actual cost trend and range (solid black line with no markers, and grey shaded area)

CAPEX and its range, it is evident that almost all the projections have been within the global cost range since 2015. However, the falling rate for cost trends tends to be milder than that of the actual CAPEX, highlighting the potential issues in cost assumptions for projections. Anticipating a reduction in the CAPEX rate based on studies, the median investment cost range for onshore wind technology is expected to be approximately 820-1570 $/kW in 2050, diverging by a factor of two.

Recent data on the required investment for onshore wind installations in China and India [48] indicate the lowest CAPEX, suggesting a more cost-effective option compared to other regions. Cost trends for both are expected to remain relatively stable until 2050, with only a marginal reduction rate of 10 % during the studied timeframe. Projection for Japan [14] is an upper outlier until the year [16]. The trend for Japan shows that projections for the year 2030 are almost half of what they have considered in 2020, recording the highest reduction rate among all other studies.

3.1.4. *Offshore wind*

Regarding offshore wind, the CAPEX projections for the year 2023 exhibited a range from 2600 to 5700 $/kW, being in the ballpark of the observed cost range (Fig. 4). With Germany [86] reflecting the lowest point and Japan [14] incurring the highest capital cost. Looking ahead, the anticipated reduction in CAPEX suggests that by 2030, the cost range will span from 1700 to 3700 $/kW. Unanimously, all studies project a decremental trend in capital costs during the studied timeframe, resulting in a projected cost range of 1300-2900 $/kW in 2050. In short, the cost projections for offshore wind technology showcase a consistent trend of reduction, signalling positive advancements in cost-effectiveness.

None of the projections assessed in this study seem to be outliers compared to the expected cost range for this technology. However, the overall average CAPEX for offshore wind technology in the current market (which is around 3500 $/kW) is considerably higher than that for onshore tech (~1300 $/kW), differing by almost 3.

3.1.5. *Li-ion battery storage*

For Li-Ion battery storage technology, the cost projections for recent years have been higher than the observed costs in the global market for the year 2023 (Fig. 5). The average projected cost range for energy CAPEX in the year 2030 is estimated to be within 125-180 $/kWh with the projections for the U.S. from NREL [77] and for the global market from IEA [46] are the upper outliers, and the global market forecast from BloombergNEF [10] is the lower outlier. Looking ahead, the anticipated reduction in energy CAPEX suggests that by 2050, the cost

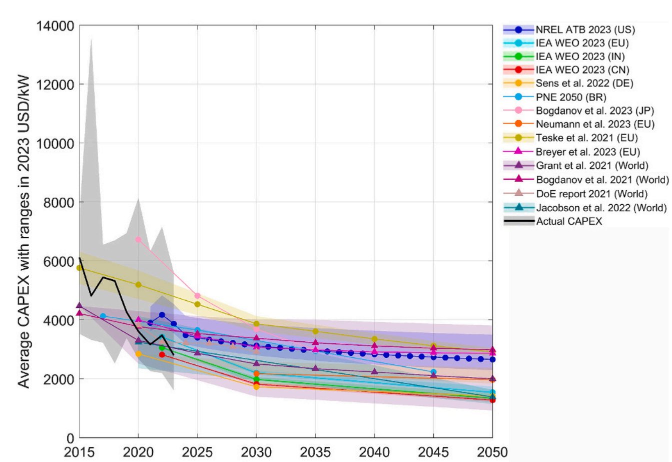

Fig. 4. Offshore wind CAPEX projection trendlines and ranges compared to the actual cost trend and range (solid black line with no markers, and grey shaded area)

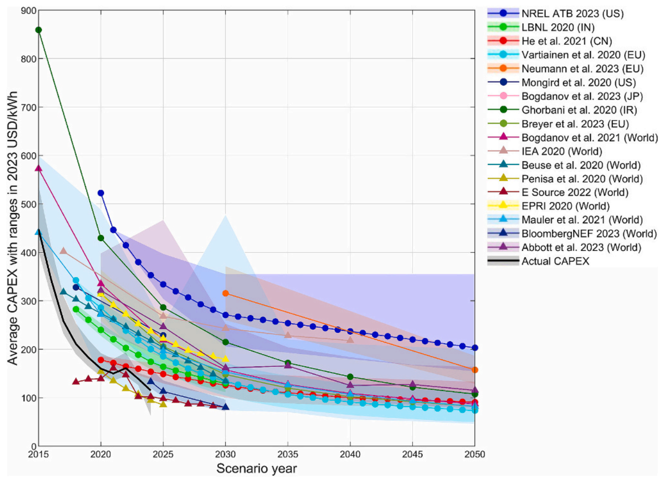

Fig. 5. Stationary Li-Ion BESS energy CAPEX (4-h) projection trendlines and ranges compared to the actual cost trend and range (solid black line with no markers)

range will span from 75 to 115 $/kWh, except for the average cost expectation for the U.S. which landed on almost 200 $/kWh.

It is visible that all datasets exhibit a reduction in investment costs throughout the studied period. Notable outliers in the cost projections for this technology are data for the IEA's global perspective and the NREL's projection for the U.S. [46,77], being higher than the majority of projected cost ranges during the studied timeframe.

3.2. Levelised costs

3.2.1. Utility-scale PV

The current LCOE of utility-scale PV systems is lower than the anticipated costs of the majority of studies, indicating the fact that most of the analysed projections are overestimating the LCOE for this technology. The solid black line, representing real LCOE data, demonstrates a notable decline in the global average levelised cost for solar PV plants, reaching 50 $/MWh in 2022 (Fig. 6). Interestingly, the dashed black line, depicting auction prices for solar PV energy, suggests more promising cost reduction prospects, giving the sense that real market prices might be lower than expected LCOE values in upcoming years. The anticipated LCOE projection for solar PV in 2030 ranges from 25 to 60 $/MWh. The average cost projections for utility-scale PV in 2050 are expected to range from 15 to 30 $/MWh, diverging by a factor of 2.

While current studies generally show proportional alignment between real LCOE and auction prices, their damping behaviour in the coming years indicates that these projections may not account for further decreases beyond 2030. The highest cost projection is attributed to the [52], which also assumes a limited potential for cost reduction compared to other studied reports. Conversely, data from Iran [38] presents the lowest projected values among the studies. Overall, all the studies expect a reduction in CAPEX in upcoming years, though being conservative on the reduction rates compared to the actual cost trend.

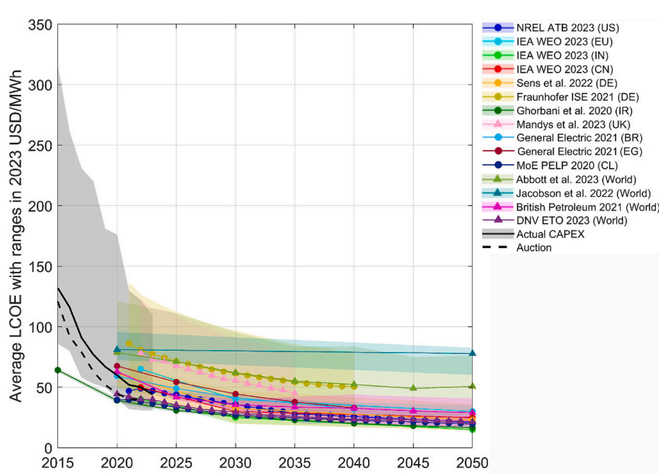

Fig. 6. Utility-scale PV LCOE projection trendlines and ranges compared to the actual cost trend (solid black line with no markers), and auction values (dashed black line with no markers)

3.2.2. Rooftop PV

The actual LCOE trend for rooftop PV technology reveals that although there was a sudden rise in 2017, the levelised cost for rooftop PV plants continued to decrease (Fig. 7). The actual average LCOE remains higher than the highest projections, which could be the result of the high dispersion of region-specific cost data inclusion in the calculation of global average LCOE for rooftop PV. Projections for the year 2024 were around 80-186 $/MWh, which were in the observed LCOE range for the same year. Limited projections currently exist for the average LCOE of rooftop solar PV in 2030, with estimates varying from 57 to 160 $/MWh. Looking ahead to 2050, global forecasts for levelised costs in rooftop PV range from 36 to 86 $/MWh diverging by a factor of around 2, which is more promising due to narrower cost ranges (around 50 $/MWh for 2050) compared to the initial years of the studied timeframe (around 100 $/MWh).

On the outliers, China [67] is showing the lowest expected LCOE during the projection timeframe in this study. Although all reports suggest an overall downward trend in LCOE, the trendlines do not indicate a significant breakdown in LCOE for rooftop PV systems beyond 2030. The projected decrease rates beyond this point appear more moderate.

3.2.3. Onshore wind

For onshore wind technology, the projected LCOE range for 2023 was estimated to be around 35-60 $/MWh (Fig. 8). The upper threshold of the expected levelised cost for onshore wind installations belongs to Europe [48], while the lowest estimation belongs to the U.S. [77]. However, almost all are above the average observed LCOE, illustrating an underestimation of the cost reduction potential for this technology. Anticipating a reduction in the LCOE rate based on studies, the median cost range for onshore wind technology is expected to be approximately 28-55 $/MWh in 2030. This decremental trend in LCOE for onshore wind technology will persist until the end of the studied timeframe, and the average levelised cost projections for onshore wind technology are expected to reach a range of 22-50 $/MWh by 2050, diverging by a

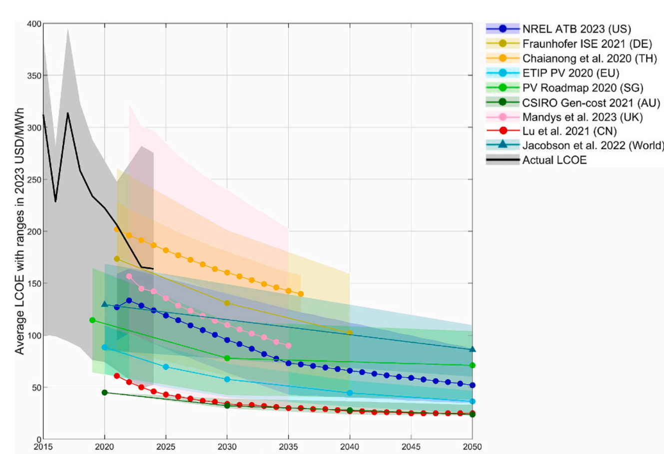

Fig. 7. Rooftop PV LCOE projection trendlines and ranges compared to the actual cost trend (solid black line with no markers)

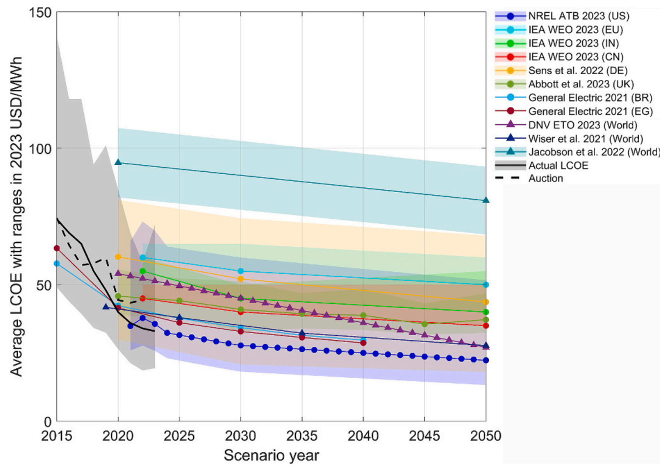

Fig. 8. Onshore LCOE projection trendlines and ranges compared to the actual cost trend (solid black line with no markers), and auction values (dashed black line with no markers)

factor of slightly more than 2.

Exceptions are IEA's cost trend for India, China, and Europe [48] that is expected to remain relatively stable until 2050, with only a marginal reduction of 5 $/MWh at maximum. Most studies show decreasing levelised costs throughout the studied period, though some outliers, such as [52] have shown considerably higher cost expectations for this technology.

3.2.4. *Offshore wind*

For offshore wind, recent LCOE estimations exhibited a range from 45 to 125 $/MWh, with Iran [38] reflecting the lowest point and [52] incurring the highest cost (Fig. 9). It is noteworthy that cost projections closely align with the actual LCOE. For instance, the observed LCOE for 2022 was around 80 $/MWh, which is obviously inside the expected levelised cost range. Looking ahead, the anticipated reduction in LCOE suggests that by 2030, the cost range will span from 40 to 120 $/MWh. Unanimously, all studies project a decremental trend in levelised costs during the studied timeframe, resulting in a projected cost range of 30-105 $/MWh in 2050.

In short, the cost projections for offshore wind technology showcase a consistent trend of reduction until the end of 2050. There are no specific outliers in the assessed projections, and all the trendlines tend to not deviate largely from the expected global average LCOE range.

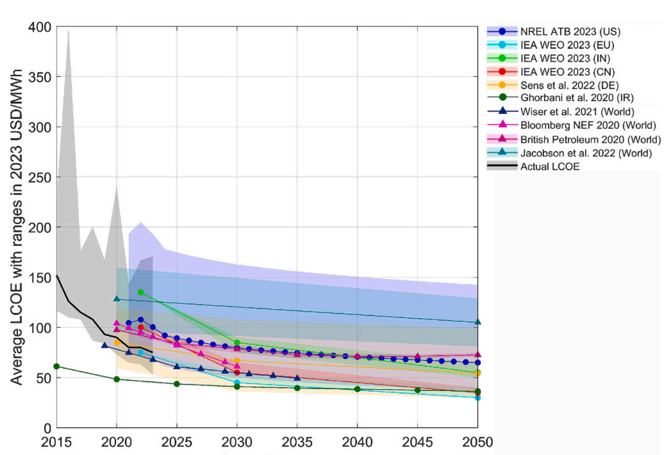

Fig. 9. Offshore wind LCOE projection trendlines and ranges compared to the actual cost trend (solid black line with no markers)

4. Discussion

4.1. *CAPEX projections agree with the overall trend of cost reductions*

Most cost projections agree on the current costs. For 2024, this can be observed in all the figures shown earlier, as all projections are within the grey area (representing the range of actual costs). This is an improvement compared to [105], where cost projections showed larger differences even to current market costs.

The studies also agree that the CAPEX for all the technologies will drop in the future. However, the average cost reduction throughout different scenarios varies strongly:

- Utility-scale PV: between 24 % (for Europe [74]) and 89 % (for a global study [41])
- Rooftop PV: between 25 % (for Europe [74]) and 88 % (for China [67])
- Onshore wind: between 7 % (for Europe [92]) and 60 % (for Japan [14])
- Offshore wind: 9 % (for Europe [74]) and 79 % (for a global study [41])
- Li-ion batteries: 28 % (for China [43]) and 89 % (for a global study [71]).

In short, almost all investment cost projections agree with the current costs and predict future reductions—though at different levels.

4.2. *CAPEX projections still too pessimistic*

Our findings show that the projections are conservative regarding the scale of potential cost reduction, which is in line with what [24] say. The recorded growth rates for the share of RE in the energy mix are considerably higher than what was estimated previously [66], contributing to these conservative approaches. Considering the case of utility-scale PV CAPEX as an example, the observed cost evolution until 2024 exceeded most of the cost reduction scenarios and is steeper than the available investment cost projections trendlines until 2050. Notable is the investment costs for solar PV modules and Li-ion stationary battery storage have almost halved within the year 2023. Today's observed CAPEX for utility-scale PV is less than 500 $/kW [100].

Exogenous factors that cause supply chain disruptions can have short-term impacts on the actual cost trends, such as the case of solar PV where module prices rose slightly in 2021 and 2022. Nonetheless, cost reductions continued in the long run due to the rapid market response to level up the supply of manufacturing material, scaled-up manufacturing capacities, and technological improvements.

Rooftop PV, onshore wind power, and stationary battery energy storage CAPEX have maintained their downward trend since 2015. CAPEX for Li-ion battery storage is also around 100 $/kWh (4-h) [82], a more than 60 % reduction from 2023. These numbers are already lower than most projected costs for 2030. However, the case is different for offshore wind power. Offshore wind power technology has longer lead times and has more project complexity compared to its onshore counterpart [89]. The CAPEX for this technology remains volatile due to the relatively smaller market compared to onshore wind power, regional complexities in offshore wind farm projects, and regional supply chain bottlenecks [4]. Overall, though, technology costs continued to fall despite volatility.

Our analysis of cost projections for RE technologies shows that newer studies have reduced estimations compared to previous studies that included data from reports published before 2020 [71,105]. Take the CAPEX of utility-scale PV for Europe as an example: [74] are using the cost assumptions provided by [26], while [92] are using the cost projections provided by [91], which in turn is using data from [36]. The main difference between the cost data for the two projections is their learning rate assumptions on the individual system components. [26]

assumes a learning rate of 25 % for PV modules, 20 % for inverters, and 10 % for the balance of the plant to develop the CAPEX projection based on the actual cost data from 2023. [36,91] are assuming a short-term learning rate of around 10 % and a long-term rate of 19-23 % for the PV modules, and 19 % for inverters. We took the case of the U.S. as a clear example of this observed deviation and will elaborate on this next.

Fig. 10 shows the CAPEX projections provided in the published Annual Technology Baseline (ATB) reports of the U.S. National Renewable Energy Laboratory (NREL) since 2015. The 2015 ATB estimated the average CAPEX for utility-scale PV to be 1500 $/kW (2024 USD) in the year 2050 [76]. Conversely, the latest report from 2024 anticipated an average of 700 $/kW (2024 USD) for the same year [78], a 53 % cost reduction. The same is true for the onshore wind technology CAPEX projection for 2050, which dropped from 2200 to 1200 $/kW (2024 USD). For offshore wind technology, it fell from 5900 to around 3300 $/kW (2024 USD).

The above shows that the updated cost projections have improved compared to previous years. Although historical costs have experienced ups and downs due to factors like supply chain disruptions and changes in raw material prices, long-term projections—based on simpler scenario designs and considering far fewer variables than real-world cost trends—still show less cost reduction compared to what has actually happened.

4.3. CAPEX projections have a large spread

In this subsection, we will discuss the outliers identified in Section 3, to explain the spread between cost projections.

Starting with the outliers of utility-scale PV CAPEX projections (recall Fig. 1), Egypt [37] has a high estimated cost due to the lower learning rates and limited installed capacity. Europe [92] has the highest values among the available projections. We suspect this is due to the use of outdated cost assumptions from the year 2015.

The global forecast for rooftop PV systems from [52], and for the U.S. [77] are the upper limit outliers in Fig. 2. The reason for higher cost expectations for this specific technology in [52] is the lower learning rate (around 9 %). For the U.S., the rooftop PV CAPEX is particularly high due to the higher soft costs (e.g., labour cost, sales) [2], resulting in limited installed capacity compared to utility-scale PV [63]. On the other hand, projections for rooftop PV CAPEX in China [67] are the lowest due to the significant installed capacity (more than 250 GW) partly driven by the presence of nationwide incentives since 2011.

For onshore wind technology (Fig. 3), projections for Japan [14] and Europe [92] are the upper outliers. [14] starts the projection with higher observed costs in 2020, but it declines rapidly as the installed capacity is expected to increase until 2035. The slight increase in CAPEX after 2035 is due to an expected disruption in the growth of installed capacity, where wind installed capacity declines beyond 2035 in a low-demand scenario.

Outliers in battery CAPEX (Fig. 5) are the projections for the U.S. [77], Europe [74], and the global projection from the IEA [46]. Projections for the U.S. are high because, in addition to the common cost components mentioned in Section 2.1, they also include other costs such as levies, integration, permitting, regulatory, and land costs. The same applies to the case of [74] as they have accounted for battery system regulatory costs in their projection for battery CAPEX. The reason for higher values in the IEA study is that they use the available cost assumptions and data from [85], which applies a learning rate of 16 % on average on the historic battery costs from 2015. While this learning rate is not necessarily inaccurate, the projection is based on higher assumed costs for 2015, thus limiting the expectations for cost reduction.

The most common reasons for misrepresenting the investment cost reduction potential of RE technologies relate to learning rate uncertainties [95], limited or outdated empirical cost data (e.g., for Li-ion batteries [46], ambiguity of system boundaries and regional factors determining the cost reduction potential of multi-component technologies [34,54] (e.g., for rooftop PV [52,67,77]).

The lack of transparency in data and methods reporting is an additional challenge. From 40 studies and 150 scenarios evaluated, only a handful of them reported their cost-forecasting methods. Almost all used a learning curve as their main method (e.g. [38,42,52,92,96]), with one study [14], merging learning curves with an expert surveying method, and a limited number only using multi-component learning rates (e.g., [46,74,77]).

4.4. LCOE projections agree with the overall trend of cost reductions

Similar to what we observed for CAPEX (Section 4.1), most LCOE projections are within the actual cost range (the grey area in Fig. 1 to Fig. 9) for the year 2024.

They also agree that the LCOE for all the technologies will drop in the future. The projected average cost levels for 2050, compared to current costs, are expressed as percentage reductions as detailed below:

- Utility-scale PV: between 4 % (for a global study [52]) and 74 % (for Iran [38])
- Rooftop PV: between 30 % (for a global study [52]) and 63 % (for the U.S. [77])
- Onshore wind: between 8 % (for Europe [48]) and 55 % (for Egypt [37])
- Offshore wind: between 16 % (for a global study [52]) and 65 % (for China [48])

In short, almost all levelised cost projections agree on current

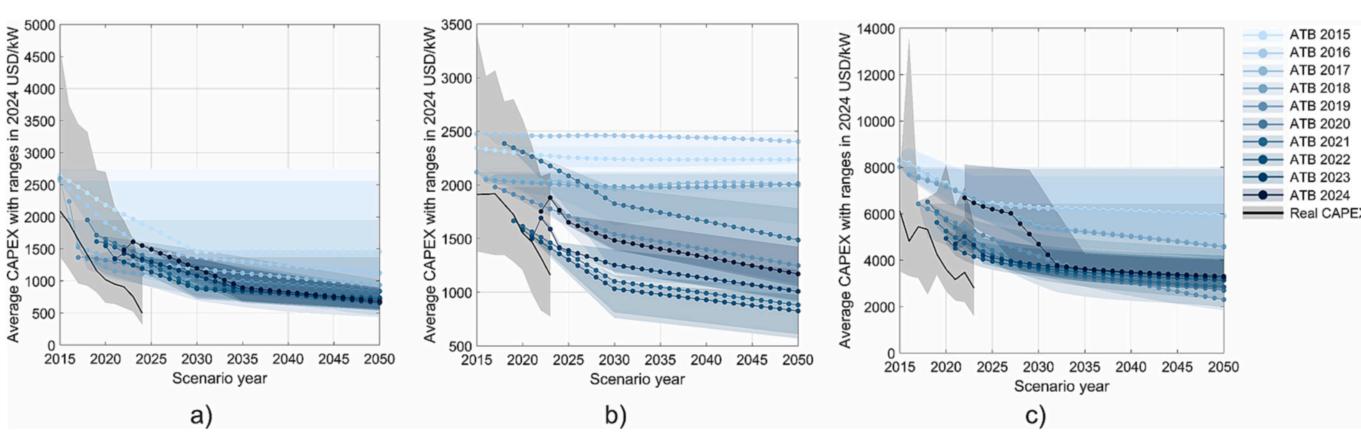

Fig. 10. CAPEX projection trendlines and ranges for the U.S. through the published NREL Annual Technology Baseline (ATB) studies since 2015 compared to the actual cost trend (solid black line with no markers) of a) utility-scale PV, b) onshore wind, and c) offshore wind.

expectations and future reductions—though with different levels of intensity.

4.5. LCOE projections are still too pessimistic

Although cost projections for all technologies are in line with actual cost ranges at the beginning of the studied timeframe, they have either underestimated (utility-scale PV, onshore, and offshore wind) or overestimated (rooftop PV) the actual cost reduction pace. Considering the case of utility-scale PV as an example, the observed reduction rate of levelised costs until 2024 exceeded most of the cost reduction scenarios. In fact, by the end of 2023, the LCOE for solar PV has dropped to one-third of its initial cost earlier in the year.

Our analysis of cost projections for RE technologies demonstrates that newer studies have reduced estimations compared to previous studies that included data from reports published before 2018 [105]. Take the LCOE of utility-scale PV for the U.S. as an example. The 2015 ATB report from the NREL estimated the average LCOE for utility-scale PV to be 91 $/MWh (2024 USD) in the year 2050 [76]. Conversely, the latest report from 2024 anticipated an average of 21 $/MWh (2024 USD) for the same year [78], a 77 % reduction. The same is true for the onshore wind technology LCOE projection for 2050, which dropped from 51 to 26 $/MWh (2024 USD). For offshore wind technology, it fell from 134 to around 75 $/MWh (2024 USD). This is evidence of updated cost assumptions and attributions incorporated into cost projection models.

In short, the more recent LCOE projections exhibit improved accuracy compared to previous versions, though they still fail to completely capture the historical trend of cost evolution in certain RE technologies for future scenarios—which is in line with our findings for CAPEX projections.

4.6. LCOE projections also have a large spread (2 to 3×)

Estimating LCOE is more complex than estimating capital costs, as various underlying factors must be considered, such as assumptions on electricity generation profiles, discount rates, and project lifetime. The inclusion of these additional parameters usually results in a different evolution trend for LCOE compared to the CAPEX of the same technology. For example, in Section 3.2, the utility-scale PV LCOE trendlines in Fig. 6 show a high estimation from [52], reflecting a higher levelised cost of delivered electricity. This projection includes infrastructure-related costs (e.g., transmission, storage), often excluded from other studies [99]. Similarly, the same study seemingly provides higher onshore wind LCOE because it accounts for these system-level costs. In contrast, the LCOE forecast for rooftop PV systems in China [67] is the lowest, driven by expectations of rapid installed capacity growth and reduced CAPEX – partly due to the nationwide incentives.

Further complicating the comparison of LCOE is the fact that capacity or plant factors are often based on highly dissimilar assumptions across studies or are excluded altogether. In systems with increasing shares of RE, the marginal energy value tends to decrease, also known as generation devaluation [65]. The declining correlation between electricity supply and demand leads to lower prices and, in the extreme, to increased curtailment, which lowers the capacity factor [27]. Therefore, overall LCOE increase, as shown in [14] on Japan's PV and onshore wind.

Excessive curtailment can be mitigated with grid flexibility measures [93]. However, only a limited number of studies have accounted for these integration costs: [52] for global costs, [77] for the U.S., and [74] for Europe, as mentioned in Section 4.3. For example, [52] factored in transmission and storage. Considering system-level costs results in higher LCOE.

The spread in LCOE projections comes from other assumptions beyond technology costs. One of them is the discount rate [90]. By definition, the discount rate significantly impacts the LCOE, especially for RE technologies (because they are capital-intensive). The discount rate should capture the cost of capital, the risk of a project, and the targeted financial return [79]. These elements are unique to a particular region (e.g., the cost of capital in Sudan is higher than in Germany [30]), project or technology (e.g., the risk of a well-established solar PV project is lower than a wave power [3]), and stakeholders (e.g., profit expectations of a private company are higher than a community-ownership model [44]). Furthermore, these elements might evolve (e.g. interest policies from central banks or decreasing risk profiles as technologies mature), although forecasting long-term interest rates is not something that can be done accurately to our understanding. It is worth noting that even modest changes in the discount rate can have a sizable effect; for instance, studies indicate that adjusting the rate by as little as 5 %-points can lead to significant reductions in LCOE, sometimes by as much as 40 % [8,33,53].

Projections often assume uniform discount rates across RE technologies, likely to facilitate generalised comparisons [12,80] and due to limited transparency in financial data specific to individual technologies and regions [75]. However, in some regions, we observed the opposite: that within the same region discount rate assumptions vary broadly. The case of Iran, for example, has assumptions from 7 % [38] to 18 % [45]. This difference is because the system ownership model in [45] is a community focusing on minimising energy costs, while in [38], the focus is on designing a national energy system development plan with lower financial return requirements (i.e., a welfare planning perspective). Similarly, within Europe, [32] assumes a 10 % discount rate as the Weighted Average Cost of Capital (WACC), while [48] considers an average of 5 % for PV technology. We suspect these disparities are present in many other regions and studies. The WACC for utility-scale PV and batteries in the U.S. is assumed to be around 3 %, which is the lowest compared to other technologies such as CSP (4 %) and geothermal (4 %) [78]. Regarding the evolution of discount rates over time, [38] mention that the current discount rates in Iran could be higher than what they have assumed, but they expect it to drop with increasing deployments of RE. Note that all the quoted rates here exclude expected capital gains and are not inflation-adjusted.

To sum up, the broad spread in LCOE projections underscores the need for greater transparency and context-specific assumptions—especially regarding discount rates, system integration costs, and regional financial conditions—to ensure that LCOE estimates meaningfully reflect the true costs and risks of RE technologies across different regions and deployment scenarios.

5. Conclusion

We systematised and analysed the cost assumptions of utility-scale photovoltaics, rooftop photovoltaics, onshore wind, offshore wind, and Li-ion batteries from 40 studies with over 150 scenarios across diverse geographical regions. We compiled Levelised Costs of Electricity (LCOE) and Capital Expenditures (CAPEX) into a database. Subsequently, we compared these values against observed market values.

Generally, projections have improved in following the actual cost trends and indicated a reduction in the LCOE and CAPEX indicators throughout the studied timeframe. However, there is a large spread between projections, and almost all are still too pessimistic. More specifically, we found that:

- Compared to older studies, more recent projections show significant cost reductions. For instance, the CAPEX projections for the U.S. for 2050 are 53 %, 48 %, and 44 % lower in a study conducted in 2024, compared to the 2015 version for utility-scale photovoltaics, onshore, and offshore wind technologies, respectively. The LCOE projections for the same two studies are 77 %, 49 %, and 44 % lower in the 2024 version for utility-scale PV, onshore, and offshore wind technologies, respectively. While the projections have improved, they are still off: most projections for 2050 are in the same ballpark as costs observed today (2024).

- Utility-solar photovoltaics and batteries CAPEX and LCOE projections are particularly pessimistic. The costs that most studies foresee for the year 2050 are already observed today or likely within reach in the next couple of years.
- Long-term estimates of CAPEX for both onshore and offshore wind technologies are above the actual observed costs. In the case of offshore wind technology, the projected cost reduction is slower than the historical cost evolution trend, though observed costs suffer from a large disparity.
- The spread in CAPEX can largely be attributed to outdated cost assumptions, and varying regional factors such as learning rates and soft costs. Variations in system boundaries and assumptions, particularly for multi-component technologies like rooftop photovoltaics and batteries, also contribute to misrepresented CAPEX reduction potential.
- The difference between the most optimistic and pessimistic LCOE projections is as large as fourfold, particularly for solar photovoltaics and offshore wind technologies. For the rooftop photovoltaics, and onshore wind, a 2× disparity is observed. Unlike rooftop photovoltaics, the majority of 2050 projections for onshore wind LCOE are at least 10 % higher than current average market values. This raises concerns about the reliability of LCOE comparisons across studies.
- A significant portion of the LCOE disparities can be attributed to differing assumptions about discount rates. Many studies apply arbitrary rates, often failing to reflect region-specific costs of capital, profit expectations, and technology-specific risks, leading to inconsistent LCOE estimates.

The case of solar PV and batteries is particularly concerning, as even the most optimistic studies predict cost levels being achieved 10 to 15 years earlier than anticipated. As the saying goes, all models are wrong, but some are useful—though in this case, the models missed the mark entirely.

CRediT authorship contribution statement

Hadi Vatankhah Ghadim: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jannik Haas:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization, Writing – original draft. **Christian Breyer:** Writing – review & editing, Validation, Resources. **Hans Christian Gils:** Writing – review & editing, Validation. **E. Grant Read:** Writing – review & editing, Validation. **Mengzhu Xiao:** Resources. **Rebecca Peer:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Writing – original draft.

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 data is uploaded to the open-access Zenodo repository: https://doi.org/10.5281/zenodo.14744022

References

[1] Abbott, B. W., Abrahamian, C., Newbold, N., Smith, P., Merritt, M., Sayedi, S. S., Bekker, J., Greenhalgh, M., Gilbert, S., King, M., Lopez, G., Zimmermann, N., & Breyer, C. (2023). Accelerating the renewable energy revolution to get Back to the Holocene. In *earth's future* (Vol. 11, issue 9). doi:https://doi.org/10.1029/2023EF003639.
[2] Agdas D, Barooah P. On the economics of rooftop solar PV adoption. Energy Policy 2023;178:113611. https://doi.org/10.1016/J.ENPOL.2023.113611.
[3] Astariz S, Iglesias G. The economics of wave energy: a review. Renew Sust Energ Rev 2015;45:397–408. https://doi.org/10.1016/J.RSER.2015.01.061.
[4] Bento N, Fontes M. Emergence of floating offshore wind energy: technology and industry. Renew Sust Energ Rev 2019;99:66–82. https://doi.org/10.1016/J.RSER.2018.09.035.
[5] Bergek A, Mignon I. Motives to adopt renewable electricity technologies: evidence from Sweden. Energy Policy 2017;106. https://doi.org/10.1016/j.enpol.2017.04.016.
[6] Beuse M, Steffen B, Schmidt TS. Projecting the competition between energy-storage Technologies in the Electricity Sector. Joule 2020;4(10). https://doi.org/10.1016/j.joule.2020.07.017.
[7] Bistline JET, Bedilion R, Goteti NS, Kern N. Implications of variations in renewable cost projections for electric sector decarbonization in the United States. IScience 2022;25(6). https://doi.org/10.1016/j.isci.2022.104392.
[8] Blyth W, Gross R, Rickman J, MacIver C, Bell K. Transition risk: investment signals in a decarbonising electricity system. Appl Energy 2023;352. https://doi.org/10.1016/j.apenergy.2023.121938.
[9] BNEF. New Energy Outlook 2021:2021 [In BNEF].
[10] BNEF. Lithium-ion battery pack prices hit record low of $139/kWh. BNEF, https://about.bnef.com/blog/lithium-ion-battery-pack-prices-hit-record-low-of-139-kwh/; 2023.
[11] BNEF. Power transition trends 2023. Bloomberg New Energy Finance, https://about.bnef.com/blog/power-transition-trends-2023/; 2023.
[12] Bogdanov D, Child M, Breyer C. Reply to 'Bias in energy system models with uniform cost of capital assumption. Nat Commun 2019;10(1):1–2. https://doi.org/10.1038/s41467-019-12469-y.
[13] Bogdanov D, Gulagi A, Fasihi M, Breyer C. Full energy sector transition towards 100% renewable energy supply: integrating power, heat, transport and industry sectors including desalination. Appl Energy 2021;283. https://doi.org/10.1016/j.apenergy.2020.116273.
[14] Bogdanov D, Oyewo AS, Mensah TNO, Nishida Y, Saito T, Aikawa T, et al. Energy transition for Japan: pathways towards a 100% renewable energy system in 2050. IET Renewable Power Generation 2023;17(13). https://doi.org/10.1049/rpg2.12844.
[15] Bosch J, Staffell I, Hawkes AD. Global levelised cost of electricity from offshore wind. Energy 2019;189. https://doi.org/10.1016/j.energy.2019.116357.
[16] BP. Energy Outlook 2020 Edition. *BP Energy Outlook* 20330, Statistical review. London: British Petroleum; 2020.
[17] Brändle G, Schönfisch M, Schulte S. Estimating long-term global supply costs for low-carbon hydrogen. Appl Energy 2021;302. https://doi.org/10.1016/j.apenergy.2021.117481.
[18] Breyer C, Bogdanov D, Ram M, Khalili S, Vartiainen E, Moser D, et al. Reflecting the energy transition from a European perspective and in the global context—relevance of solar photovoltaics benchmarking two ambitious scenarios. Prog Photovolt Res Appl 2023;31(12). https://doi.org/10.1002/pip.3659.
[19] Breyer C, Khalili S, Bogdanov D, Ram M, Oyewo AS, Aghahosseini A, et al. On the history and future of 100% renewable energy systems research. IEEE Access 2022;10. https://doi.org/10.1109/ACCESS.2022.3193402.
[20] Brown TW, Bischof-Niemz T, Blok K, Breyer C, Lund H, Mathiesen BV. Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems.'. Renew Sust Energ Rev 2018;92. https://doi.org/10.1016/j.rser.2018.04.113.
[21] Chaianong A, Bangviwat A, Menke C, Breitschopf B, Eichhammer W. Customer economics of residential PV–battery systems in Thailand. Renew Energy 2020;146. https://doi.org/10.1016/j.renene.2019.06.159.
[22] Come Zebra EI, van der Windt HJ, Nhumaio G, Faaij APC. A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries. Renew Sust Energ Rev 2021;144:111036. https://doi.org/10.1016/J.RSER.2021.111036.
[23] Creutzig, F., Agoston, P., Goldschmidt, J. C., Luderer, G., Nemet, G., & Pietzcker, R. C. (2017). The underestimated potential of solar energy to mitigate climate change. In *nature energy* (Vol. 2, issue 9). doi:https://doi.org/10.1038/nenergy.2017.140.
[24] Creutzig F, Hilaire J, Nemet G, Müller-Hansen F, Minx JC. Technological innovation enables low cost climate change mitigation. In Energy Research and Social Science 2023;105. https://doi.org/10.1016/j.erss.2023.103276.
[25] David LO, Nwulu NI, Aigbavboa CO, Adepoju OO. Integrating fourth industrial revolution (4IR) technologies into the water, energy & food nexus for sustainable security: a bibliometric analysis. J Clean Prod 2022;363:132522. https://doi.org/10.1016/J.JCLEPRO.2022.132522.
[26] DEA. Technology data for generation of electricity and district heating. In Technology Data Catalogue for Electricity and district heating production 2018; 2018. https://ens.dk/sites/ens.dk/files/Analyser/technology_data_catalogue_for_el_and_dh.pdf.

[27] Denholm P, Clark K, O'Connell M. On the Path to SunShot: Emerging issues and challenges in integrating high levels of solar into the electrical generation and transmission system. 2016. doi:10.2172/1253978.

[28] Deorah SM, Abhyankar N, Arora S, Gambhir A, Phadke A. Estimating the cost of grid-scale Lithium-ion battery storage in India energy technologies area Lawrence Berkeley National Laboratory. 2020.

[29] DNV. Energy transition outlook 2023: A global and regional forecast to 2050. Remi Eriksen: DNV; 2023.

[30] Egli F, Steffen B, Schmidt TS. Bias in energy system models with uniform cost of capital assumption. Nature Communications 2019 10:1 2019;10(1):1–3. https://doi.org/10.1038/s41467-019-12468-z.

[31] EPRI. Battery energy storage Lifecyle cost assessment summary. 2020.

[32] ETIP. Fact sheets about photovoltaics. European Technology & Innovation Platform; 2020. https://etip-pv.eu/publications/etip-pv-publications/download/pv-the-cheapest-electricity-source-almost-everyw-2.

[33] Falchetta G, Michoud B, Hafner M, Rother M. Harnessing finance for a new era of decentralised electricity access: a review of private investment patterns and emerging business models. Energy Res Soc Sci 2022;90. https://doi.org/10.1016/j.erss.2022.102587.

[34] Fallah ardashir, J. F., & Ghadim, H. V.. Large-scale energy storages in joint energy and ancillary multimarkets. In *energy storage in energy*. Markets: Uncertainties, Modelling, Analysis and Optimization; 2021. https://doi.org/10.1016/B978-0-12-820095-7.00017-0.

[35] Fallah Ardashir J, Vatankhah Ghadim H. Introduction and literature review of cost-saving characteristics of multi-carrier energy networks. In Power Systems 2021. https://doi.org/10.1007/978-3-030-60086-0_1.

[36] Fraunhofer ISE. Current and future cost of photovoltaics. Long-term scenarios for market development, system prices and LCOE of utility-scale PV systems. Agora Energiewende, February; 2015.

[37] General Electric. Accelerated growth of renewables and gas power can rapidly change the trajectory on climate change. 2021. https://www.ge.com/content/dam/gepower-new/global/en_US/downloads/gas-new-site/future-of-energy/ge-future-of-energy-white-paper.pdf.

[38] Ghorbani N, Aghahosseini A, Breyer C. Assessment of a cost-optimal power system fully based on renewable energy for Iran by 2050 – achieving zero greenhouse gas emissions and overcoming the water crisis. Renew Energy 2020;146. https://doi.org/10.1016/j.renene.2019.06.079.

[39] Gordon D. Battery market forecast to 2030: pricing, capacity, and supply and demand. E Source 2022. https://www.esource.com/report/130221hvfd/battery-market-forecast-2030-pricing-capacity-and-supply-and-demand.

[40] Graham P, Hayward J, Foster J, Havas L. GenCost 2020-21: Final report. June: CSIRO; 2021. p. 1–85. https://publications.csiro.au/publications/publication/PIcsiro:EP2021-0160/SQgencost/RP1/RS25/RORECENT/STsearch-by-keyword/LISEA/RI1/RT6.

[41] Grant N, Hawkes A, Napp T, Gambhir A. Cost reductions in renewables can substantially erode the value of carbon capture and storage in mitigation pathways. One Earth 2021;4(11). https://doi.org/10.1016/j.oneear.2021.10.024.

[42] Gulagi A, Ram M, Bogdanov D, Sarin S, Mensah TNO, Breyer C. The role of renewables for rapid transitioning of the power sector across states in India. Nat Commun 2022;13(1). https://doi.org/10.1038/s41467-022-33048-8.

[43] He X, Ou S, Gan Y, Lu Z, Przesmitzki SV, Bouchard JL, et al. Greenhouse gas consequences of the China dual credit policy. Nat Commun 2020;11(1). https://doi.org/10.1038/s41467-020-19036-w.

[44] Hogan JL, Warren CR, Simpson M, McCauley D. What makes local energy projects acceptable? Probing the connection between ownership structures and community acceptance. Energy Policy 2022;171:113257. https://doi.org/10.1016/J.ENPOL.2022.113257.

[45] Hosseini SJAD, Moazzami M, Shahinzadeh H. Optimal sizing of an isolated hybrid wind/PV/battery system with considering loss of power supply probability. Majlesi J Electrical Eng 2017;11(3).

[46] IEA. Levelised Cost of Electricity Calculator. In *Levelised Cost of Electricity Calculator*. 2020.

[47] IEA. India Energy Outlook. In *World Energy Outlook Special Report*. 2021.

[48] IEA. World Energy Outlook 2023:2023. https://www.iea.org/reports/world-energy-outlook-2023.

[49] Insel MA, Sadikoglu H, Melikoglu M. Assessment and determination of 2030 onshore wind and solar PV energy targets of Türkiye considering several investment and cost scenarios. Results in Eng 2022;16. https://doi.org/10.1016/j.rineng.2022.100733.

[50] IRENA. Renewable Power Generation Costs in 2024:2023. https://www.irena.org/Publications/2024/Sep/Renewable-Power-Generation-Costs-in-2023.

[51] Jacobson MZ, Delucchi MA, Cameron MA, Frew BA. The United States can keep the grid stable at low cost with 100% clean, renewable energy in all sectors despite inaccurate claims. Proc Natl Acad Sci USA 2017;114(26). https://doi.org/10.1073/pnas.1708069114.

[52] Jacobson MZ, von Krauland AK, Coughlin SJ, Dukas E, Nelson AJH, Palmer FC, et al. Low-cost solutions to global warming, air pollution, and energy insecurity for 145 countries. Energy Environ Sci 2022;15(8). https://doi.org/10.1039/d2ee00722c.

[53] Jamil SR, Wang L, Tang C, Khan HMS, Che D. The role and impact of costing method in the decision-making of energy project: a comparative assessment between levelized cost of energy and benefit-to-cost ratio analysis. Int J Energy Res 2022;46(4). https://doi.org/10.1002/er.7470.

[54] Junginger M, Louwen A. Technological learning in the transition to a low-carbon energy system: conceptual issues, empirical findings, and use in energy modeling. In Technological Learning in the Transition to a Low-Carbon Energy System: Conceptual Issues, Empirical Findings, and Use, in Energy Modeling 2019. https://doi.org/10.1016/C2018-0-04547-8.

[55] Kost C, Shammugam S, Fluri V, Peper D, Memar AD, Schlegel T. *Levelized cost of electricity- renewable energy technologies June 2021* (issue June, pp. 1–45). Fraunhofer ISE; 2021.

[56] Lazard. Levelized Cost of Energy Analysis v9.0 2015. https://www.lazard.com/research-insights/levelized-cost-of-energyplus/; 2015.

[57] Lazard. Levelized cost of energy analysis v10.0 2016. *Lazard, 10.0*(December 2016). 2016.

[58] Lazard.. Levelized cost of energy analysis v11.0 2017. Lazard; 2017.

[59] Lazard. Levelized Cost of Energy Analysis v12.0 2018. *Lazard's Levelized Cost of Storage - Version 12.0, November*. 2018.

[60] Lazard. Levelized Cost of Energy Analysis v13.0 2019. Lazard.Com, November. 2019.

[61] Lazard.. Levelized cost of energy analysis v14.0 2020. Lazard Freres & Co 2020; 11(November).

[62] Lazard. Levelized Cost of Energy Analysis v15.0 2021. Lazard, [October 2021]. 2021.

[63] Lazard. Levelized Cost of Energy Analysis v16.0 2023. 2023.

[64] Lazard. Levelized Cost of Energy (LCOE+) Analysis v17.0 2024. *Lazard, April, 12*. 2024.

[65] Loth E, Qin C, Simpson JG, Dykes K. Why we must move beyond LCOE for renewable energy design. In Adv Appl Energy 2022;8. https://doi.org/10.1016/j.adapen.2022.100112.

[66] Louwen A, Junginger M. Deriving experience curves and implementing technological learning in energy system models. In *The Future European Energy System:* Renewable Energy, Flexibility Options and Technological Progress. 2021. https://doi.org/10.1007/978-3-030-60914-6_4.

[67] Lu X, Chen S, Nielsen CP, Zhang C, Li J, Xu H, et al. Combined solar power and storage as cost-competitive and grid-compatible supply for China's future carbon-neutral electricity system. Proc Natl Acad Sci USA 2021;118(42). https://doi.org/10.1073/pnas.2103471118.

[68] Ma R, Cai H, Ji Q, Zhai P. The impact of feed-in tariff degression on R&D investment in renewable energy: the case of the solar PV industry. Energy Policy 2021;151. https://doi.org/10.1016/j.enpol.2021.112209.

[69] Mai T, Bistline J, Sun Y, Cole W, Marcy C, Namovicz C, et al. The role of input assumptions and model structures in projections of variable renewable energy: a multi-model perspective of the U.S. electricity system. Energy Econ 2018;76. https://doi.org/10.1016/j.eneco.2018.10.019.

[70] Mandys F, Chitnis M, Silva SRP. Levelized cost estimates of solar photovoltaic electricity in the United Kingdom until 2035. Patterns 2023;4(5). https://doi.org/10.1016/j.patter.2023.100735.

[71] Mauler L, Duffner F, Zeier WG, Leker J. Battery cost forecasting: a review of methods and results with an outlook to 2050. In. Energy Environ Sci 2021;14(9). https://doi.org/10.1039/d1ee01530c.

[72] MME, & EPE. Plano Nacional de Energia - PNE 2050. Plano Nacional de Energia - PNE 2050 2020;*53*(9).

[73] Mongird, K., Viswanathan, V., Balducci, P., Alam, J., Fotedar, V., Koritarov, V., & Hadjerioua, B. (2020). An evaluation of energy storage cost and performance characteristics. In *energies* (Vol. 13, issue 13). doi:https://doi.org/10.3390/en13133307.

[74] Neumann F, Zeyen E, Victoria M, Brown T. The potential role of a hydrogen network in Europe. Joule 2023;7(8). https://doi.org/10.1016/j.joule.2023.06.016.

[75] Nicoli M, Colucci G, Di Cosmo V, Lerede D, Savoldi L. Evaluating the impact of hurdle rates on the Italian energy transition through TEMOA. Appl Energy 2025; 377:124633. https://doi.org/10.1016/j.apenergy.2024.124633.

[76] OEDI. 2015 annual technology baseline (ATB) cost and performance data for electricity generation technologies. Open Energy Data Initiative (OEDI) 2015. https://www.nrel.gov/docs/fy15osti/64077-DA.xlsm.

[77] OEDI. (2023). 2023 annual technology baseline (ATB) cost and performance data for electricity generation technologies. Open Energy Data Initiative (OEDI).

[78] OEDI. 2024 annual technology baseline (ATB) cost and performance data for electricity generation technologies. Open Energy Data Initiative (OEDI) 2024. https://atb.nrel.gov/electricity/2024/index.

[79] Osiolo HH. Impact of cost, returns and investments: towards renewable energy generation in sub-Saharan Africa. Renew Energy 2021;180:756–72. https://doi.org/10.1016/J.RENENE.2021.08.082.

[80] Ouyang X, Lin B. Levelized cost of electricity (LCOE) of renewable energies and required subsidies in China. Energy Policy 2014;70. https://doi.org/10.1016/j.enpol.2014.03.030.

[81] Penisa XN, Castro MT, Pascasio JDA, Esparcia EA, Schmidt O, Ocon JD. Projecting the price of lithium-ion NMC battery packs using a multifactor learning curve model. Energies 2020;13(20). https://doi.org/10.3390/en13205276.

[82] Rayner T. Energy storage installations rise 61% this year. Pv Magazine 2024. https://www.pv-magazine.com/2024/08/15/energy-storage-installations-rise-61-this-year/.

[83] Ringkjøb HK, Haugan PM, Solbrekke IM. A review of modelling tools for energy and electricity systems with large shares of variable renewables. In. Renew Sust Energ Rev 2018;96. https://doi.org/10.1016/j.rser.2018.08.002.

[84] Robert B, Brown EB. Proyecciones de costos inversión y LCOE. 2021. https://energia.gob.cl/pelp/proyecciones-de-costos.

[85] Schmidt, O., Hawkes, A., Gambhir, A., & Staffell, I. (2017). The future cost of electrical energy storage based on experience rates. In *Nat Energy* (Vol. 2, issue 8). doi:https://doi.org/10.1038/NENERGY.2017.110.

[86] Sens L, Neuling U, Kaltschmitt M. Capital expenditure and levelized cost of electricity of photovoltaic plants and wind turbines – development by 2050. Renew Energy 2022;185. https://doi.org/10.1016/j.renene.2021.12.042.
[87] SERIS. UPDATE of the Solar Photovoltaic (PV) Roadmap for Singapore. https://www.seris.nus.edu.sg/doc/publications/Update-of-the-Solar-Roadmap-for-Singapore-(March-2020).pdf; 2020.
[88] Shen W, Chen X, Qiu J, Hayward JA, Sayeef S, Osman P, et al. A comprehensive review of variable renewable energy levelized cost of electricity. Renew Sust Energ Rev 2020;133:110301. https://doi.org/10.1016/J.RSER.2020.110301.
[89] Sovacool BK, Enevoldsen P, Koch C, Barthelmie RJ. Cost performance and risk in the construction of offshore and onshore wind farms. Wind Energy 2017;20(5). https://doi.org/10.1002/we.2069.
[90] Steffen B. Estimating the cost of capital for renewable energy projects. Energy Econ 2020;88. https://doi.org/10.1016/j.eneco.2020.104783.
[91] Steurer M, Brand H, Blesl M, Borggrefe F, Fahl U, Fuchs AL, et al. Energiesystemanalyse Baden-Württemberg: Datenanhang zu techoökonomischen Kenndaten. Ministerium für Umwelt Klima und Energiewirtschaft Baden-Württemberg, STrise: Universität Stuttgart. *Deutsches Zentrum Für Luft-Und Raumfahrt, Zentrum Für Sonnenenergie-Und Wasserstoff-Forschung Baden-Württemberg:* Stuttgart, Germany. https://elib.dlr.de/126728/1/Energiesystemanalyse_Baden-Wu_rttemberg_Schlussbericht_Homepage.pdf; 2018.
[92] Teske S, Pregger T, Simon S, Naegler T, Pagenkopf J, Deniz Ö, et al. It is still possible to achieve the Paris climate agreement: regional, sectoral, and land-use pathways. Energies 2021;14(8). https://doi.org/10.3390/en14082103.
[93] Ueckerdt F, Hirth L, Luderer G, Edenhofer O. System LCOE: what are the costs of variable renewables? Energy 2013;63. https://doi.org/10.1016/j.energy.2013.10.072.
[94] DoE US. Financial incentives for hydrogen and fuel cell projects. 2022. https://www.energy.gov/eere/fuelcells/financial-incentives-hydrogen-and-fuel-cell-projects.
[95] van Sark W, Nemet G, Kahouli-Brahmi S, Wene CO, Neij L. General aspects and caveats of experience curve analysis. Technological learning in the energy sector. Edward Elgar Publishing; 2010.
[96] Vartiainen E, Breyer C, Moser D, Medina ER, Busto C, Masson G, et al. True cost of solar hydrogen-Levelised cost of hydrogen in Europe 2021-2050. Proceedings/38th European Photovoltaic Solar Energy Conference and Exhibition-ISBN: 3-936338-78-7 2021:1601–7.
[97] Vartiainen E, Masson G, Breyer C, Moser D, Román Medina E. Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity. Prog Photovolt Res Appl 2020;28(6). https://doi.org/10.1002/pip.3189.
[98] Vatankhah Ghadim H. *Renewable Electricity technology cost dataset - V1.0*. Zenodo. 2025. https://doi.org/10.5281/zenodo.14744023.
[99] Vatankhah Ghadim H, Fallah Ardashir J, Odonkor P. Effective factors and policies in electrical energy security. In The Handbook of Energy Policy 2023. https://doi.org/10.1007/978-981-19-6778-8_5.
[100] VDMA. International Technology Roadmap for Photovoltaics (ITRPV) - 2023 Results. https://www.vdma.org/international-technology-roadmap-photovoltaic; 2024.
[101] Victoria, M., Haegel, N., Peters, I. M., Sinton, R., Jäger-Waldau, A., del Cañizo, C., Breyer, C., Stocks, M., Blakers, A., Kaizuka, I., Komoto, K., & Smets, A. (2021). Solar photovoltaics is ready to power a sustainable future. In *joule* (Vol. 5, issue 5). doi:https://doi.org/10.1016/j.joule.2021.03.005.
[102] Viswanathan V, Mongird K, Franks R, Li X, Sprenkle V, Baxter R. 2022 grid energy storage technology cost and performance assessment. 2022.
[103] Way R, Ives MC, Mealy P, Farmer JD. Empirically grounded technology forecasts and the energy transition. Joule 2022;6(9). https://doi.org/10.1016/j.joule.2022.08.009.
[104] Wiser R, Rand J, Seel J, Beiter P, Baker E, Lantz E, et al. Expert elicitation survey predicts 37% to 49% declines in wind energy costs by 2050. Nat Energy 2021;6(5). https://doi.org/10.1038/s41560-021-00810-z.
[105] Xiao M, Junne T, Haas J, Klein M. Plummeting costs of renewables - are energy scenarios lagging? Energ Strat Rev 2021;35. https://doi.org/10.1016/j.esr.2021.100636.
[106] Yao Y, Xu JH, Sun DQ. Untangling global levelised cost of electricity based on multi-factor learning curve for renewable energy: wind, solar, geothermal, hydropower and bioenergy. J Clean Prod 2021;285:124827. https://doi.org/10.1016/J.JCLEPRO.2020.124827.