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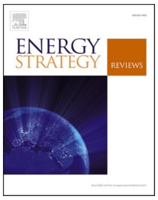

Plummeting costs of renewables - Are energy scenarios lagging?

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A B S T R A C T

Wind and solar energy play a pivotal role in deep decarbonization pathways for the future. However, energy scenario studies differ substantially in the contribution of these technologies, as the technology selection in models strongly depends on the choice of techno-economic parameters. In this article, we systematically compare the cost assumptions for solar and wind technologies in global, regional and national energy scenario studies with costs observed in reality and with recent remuneration from market auctions. Specially, we compared the capital expenditure (CAPEX) and the levelized cost of electricity (LCOE) towards the year of 2050 when available with historical market prices and auction prices. Our results indicate that the trend of rapid cost declines has been structurally underestimated in virtually all future energy scenario analyses and suggest that even the most recent studies refer to obsolete or very conservative values. This leads to underestimating the future role and level of deployment of renewable technologies. We recommend an open database for costs of renewable technologies to enhance the accuracy and transparency of future energy scenarios.

1. Introduction

To achieve the 1.5- to 2.0-degree climate target, enormous efforts must be made to transform the energy system, potentially leading to the need for net negative emissions depending on the speed and time of emission reduction interventions [1,2]. Energy scenarios are an approach to assess these paths and to find ways how such a transformation can succeed (e.g. Refs. [3–7]). However, if the deployment of renewables is retrospectively compared to global energy scenarios from recent years, it can be observed that the expansion of renewables has often been underestimated. For example, the globally installed capacity of photovoltaics (PV) has shown an average annual growth of 38% per year between 1998 and 2015, while the International Energy Agency (IEA) has repeatedly projected growths of 16–30% per year [8]. From the perspective of scenario studies, reasons for such a difference can be diverse: potential interests from industry and politics in scenario modeling [8], lack of inclusion of "real world" non-monetary preferences and public incentive schemes [9], or rapid technological and institutional learning which lead to stronger cost decreases than assumed. The latter play a decisive role in model-based energy scenarios, especially in optimization models in which the structure of recommended technology portfolios is strongly driven by the techno-economic assumptions [10]. Yet, literature that points to the cost reduction potentials of Renewable Energy Technologies (RET) (such as [11–13]) often do not seem to be integrated into energy system models and scenario studies fast enough. The foresight offered by the energy planning community was, therefore, not a reliable guide for decision-makers in energy policy and economics.

Recently, many countries in the world have shifted renewable energy support schemes in favor of tenders [14,15]. Here, the level of incentive or to-be-paid energy price is determined by market auctions. Especially in the last years, the winning bids of wind parks, solar photovoltaics, and concentrated solar power have shown consistent low-price outcomes and continuously surprised the energy planning community [16]. It is not rare to observe, say, 10-year cost-forecasts for these energy technologies being underpassed by current tenders [17–19]. Those tenders seem to have accelerated the energy transition and the rise of renewables in recent years [20].

In this article, we want to systematically assess cost assumptions for RET in energy scenarios by comparing them with newfound insights from real market data and auction prices. Concretely, we aim to:

- understand to what extent assumptions on investment cost in energy scenarios studies differ from real market data, and to
- compare the levelized cost of electricity (LCOE) values from the literature with prices from market auctions.

By doing so, we point to potential biases influencing scenario studies. To our knowledge, such a systematic cost assumption comparison has

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Nomenclature

AEO	Annual Energy Outlook
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CREO	China Renewable Energy Outlook
CSP	Concentrated Solar Power
E[R]	Energy [R]evolution
IEA	International Energy Agency
IESS	India Energy Security Scenarios
IRP	Integrated Resource Plan
LCOE	Levelized Cost of Electricity
LDF	Leonardo DiCaprio Foundation
O&M	Operation and Maintenance
RET	Renewable Energy Technologies
WACC	Weighted Average Cost of Capital
WEO	World Energy Outlook

not been carried out yet in the scientific literature. We provide energy system modelers and experts new insights on potential cost decreases and recommend an open database for costs of renewable technologies to enhance the accuracy and transparency of future energy scenarios.

The next section shows our methods for systematic comparison. Section 3 shows the resulting systemization of capital costs and levelized energy costs. Section 4 discusses the results and limitations, and section 5 draws our conclusions.

2. Methods

We will compare the cost assumptions used in energy scenarios to historically reported cost values. We will first elaborate on what values are obtained from the literature on energy scenarios and then explain the sources from historical costs.

Cost assumptions in model-based energy scenarios are usually reported in two ways - as capital expenditure (CAPEX), or as LCOE. We use these two metrics because both have specific strengths and weaknesses [4]. Renewables, compared to fossil technologies, have proportionately high initial investments (the major expenditure is the plant itself) but low operating costs (no fuels needed). CAPEX is, therefore, the most important cost driver for renewable technologies with the advantage of not being region-specific and needing very little assumptions.

LCOE considers many factors (project lifetime, local renewable resource, cost of capital, insurance, etc.), making it more comprehensive. The resulting value is a clear number that ultimately determines whether a technology is built or recommended by energy system models. But the many assumptions impacting the unit cost of energy generation, also make LCOE more difficult to compare. Factors such as country-specific financing mechanisms, existence of a competitive supplier industry, access to the world renewable energy market, further difficult the comparability among studies.

We have selected scenario studies that:

- include a long-term scenario of the energy system including the capacity structure for the power plant fleet,
- report renewable energy technologies cost values (either in CAPEX or LCOE),
- were published in 2015 or later (i.e. after the Paris Agreement),
- have a global, continental, or national scope (and not smaller) only if the remuneration for renewables has been set by tenders; relevant countries or regions were sourced from Ref. [17] (see Table 2).

Table 1 lists the studies that matched the above criteria and are thus part of the review. There are six regional or national studies that cover the USA, China, Europe Union, India, Brazil, and South Africa, while the rest are on global. The studies were published by scientific researchers, government bodies, or non-governmental organizations.

The considered solar and wind technologies vary across studies. Some do not differentiate among available PV, concentrated solar power (CSP), and wind technologies; some provide much more details. In particular for PV, for example, in addition to centralized utility scale or decentralized plants, a distinction was made in LUT, 100% Jac. and IRP between various other sub-technologies. CSP was not included in the study of EU and AIM/CGE. Some specify the costs of CSP with and without storage (IESS, IRP, and 100% Jac.) while others do not mention that difference. Thus, type and considered components of CSP plants in some studies are unclear.

Based on the data availability, we focus on renewable power generation of utility-scale PV, CSP, and on- and offshore wind. As some reports were limited in terms of transparency of cost data, sometimes own judgments had to be made to allow for a consolidated comparison. These mainly include considering PV as utility-scale (when no specification was made) and ignoring wind costs that were not specified as onshore or offshore. The studies 100% Jac. and 100% LUT list several types of utility-scale PV systems (each with different costs). For these, we calculated a cost average weighting by the installed capacity of each technology.

Most scenarios in our analysis exhibited a certain bandwidth of cost assumptions by region or sub-technology. Here, the (global) mean values and the cost ranges are shown for comparability in single, consolidated figures. Most studies cover the period until 2050. Our analysis focuses on that period accordingly. Exceptions are the WEO studies [21,22], IESS [23], and Luderer et al. [24], which have a time horizon until 2040, 2047, and 2100 respectively. The data can be accessed online [25]. It contains costs data for utility PV, CSP, onshore and offshore wind derived from reviewed energy scenario studies.

The capital cost assumptions from energy scenarios will be compared against investment costs as reported by the industry in the last years. And the assumptions on LCOE will be compared with the market auctions. Both comparisons should offer valuable insight into the cost trends of past years. All values are taken from the cost review of the International Renewable Energy Agency (IRENA) [17]. More precisely, from that source [17], we took two datasets:

- the CAPEX and LCOE database (that we will here call REF1) spanning from 2010 to 2018, and
- the auction database (that we will here call REF2), which includes the costs for solar PV and onshore wind (from 2010 to 2020), CSP (from 2019 to 2021), and offshore wind (2019–2020).

After extracting these cost assumptions (CAPEX and auctions) from the scenario documents, the values were converted to US-$ and adjusted for inflation to the year 2018.

3. Results

We systematically compare the cost assumptions in energy scenarios with costs reported by the industry. Investment costs will be studied in section 3.1 and the levelized costs of energy in section 3.2.

Along these sections, we will use plots that are all similarly structured. They show on their x-axis the time horizon (from 2010 to 2050) and on their y-axis the ranges of costs. The different series correspond to the selected studies. Recall that REF1 and REF2 correspond to the historical investment costs and the historical auctions, respectively, as reported by IRENA [17]. The shaded areas correspond to cost-sensitivities in the different studies.

For solar PV and onshore wind, the reference costs are also available for specific countries or regions. For the sake of readability, these values are not included in the figures, but are listed in Table 2. Studies marked with “*” indicate that there are no cost ranges available.

Table 1
Overview of reviewed energy scenario studies.

Study abbreviation	Scenario study	Geographical scope	Published year	Author/Institute	Considered technology		
					PV	CSP	Wind
AEO [26]	Annual Energy Outlook	USA	2017	The U.S Energy Information Administration (EIA)	Not specified	Not specified	Onshore wind; Offshore wind
CREO [27]	China Renewable Energy Outlook 2017	China	2017	Energy Research Institute of Academy of Macroeconomic Research/NDRC & China National Renewable Energy Centre	Centralized PV; Distributed PV	Not specified	Onshore wind standard wind turbine; Onshore wind low-speed wind turbine; Offshore wind
EU [28]	EU Reference Scenario 2016	Europe Union	2016	European Commission	PV (Northern EU); PV (Southern EU)	Not considered	Onshore wind; Offshore wind
IESS [23]	India Energy Security Scenarios 2047	India	2015	Government of India, Energy Division	Centralized PV; distributed PV	With storage; Without storage	Onshore wind; Offshore wind
E[R] Brazil [29]	Energy [R]evolution Brazil	Brazil	2016	Greenpeace	Not specified	Not specified	Onshore wind; Offshore wind
IRP [30]	Integrated Resource Plan	South Africa	2017	Department of Energy, South Africa	PV (tracking, fixed tilt)	CSP Trough (3 h, 6 h, 9 h storage); CSP Tower (3 h, 6 h, 9 h storage)	Not specified
100% Jac [31].	100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World	World	2017	Jacobson et al.	PV utility crystalline tracking; PV utility thin-film tracking	CSP no storage; CSP with storage	Onshore wind; Offshore wind
LDF [2]	Achieving the Paris Climate Agreement Goals	World	2019	Leonardo DiCaprio Foundation (LDF)	Not specified	Not specified	Onshore wind; Offshore wind
E[R] [5]	Energy [R]evolution	World	2015	Greenpeace	Not specified	Not specified	Onshore wind; Offshore wind
100% LUT '17 [32]	Global Energy System Based on 100% Renewable Energy - Power Sector	World	2017	LUT & Energy Watchgroup	PV rooftop - residential, commercial, industrial; PV optimally tilted; PV single-axis tracking	CSP (solar field, parabolic trough) with storage	Onshore wind
100% LUT '19 [33]	New Study: Global Energy System based on 100% Renewable Energy	World	2019				Onshore wind; Offshore wind
WEO NP '17 [21]	World Energy Outlook_**New Policies Scenario**	World	2017	International Energy Agency (IEA)	PV-buildings; PV-large scale	Not specified	Onshore wind; Offshore wind
WEO 450 '17 [21]	World Energy Outlook_**450 Scenario**	World	2017				
WEO NP '18 [22]	World Energy Outlook_**New Policies Scenario**	World	2018				
AIM/CGE [24]	Assessment of wind and solar power in global low-carbon energy scenarios: An introduction_**AIM/CGE model**	World	2017	Luderer et al.	Not specified	Not considered	Onshore wind
IMAGE [24]	Assessment of wind and solar power in global low-carbon energy scenarios: An introduction_**IMAGE model**	World	2017			Not specified	Onshore wind; Offshore wind
MESSAGE [24]	Assessment of wind and solar power in global low-carbon energy scenarios: An introduction_**MESSAGE model**	World	2017				Onshore wind; Offshore wind
POLES [24]	Assessment of wind and solar power in global low-carbon energy scenarios: An introduction_**POLES model**	World	2017				Onshore wind; Offshore wind
REMIND [24]	Assessment of wind and solar power in global low-carbon energy scenarios: An introduction_**REMIND model**	World	2017				Onshore wind
WITCH [24]	Assessment of wind and solar power in global low-carbon energy scenarios: An introduction_**WITCH model**	World	2017				Onshore wind; Offshore wind
REF 1 [17]	Renewable Power Generation Costs in 2018 (Cost database)	World	2018	International Renewable Energy Agency (IRENA)	Utility scale PV	Not specified	Onshore wind; Offshore wind
REF 2 [17]	Renewable Power Generation Costs in 2018 (Auction database)	World	2018				

Table 2
Historical country- or region-specific costs data for solar PV and onshore wind for 2010 and 2018 [17].

	Solar PV					Onshore Wind			
	CAPEX (2018 $/kW)		LCOE (2018 $/kWh)			CAPEX (2018 $/kW)		LCOE (2018 $/kWh)	
Country	2010	2018	2010	2018	Country/Region	2010	2018	2010	2018
China	3878	879	296	66	China	1463	1173	69	47
France	5374	1074	344	87	India	1386	1201	81	61
Germany	3640	1113	327	112	Brazil	2492	1823	92	60
India	4963	793	299	62	Central America and the Caribbean	2614	1788	84	58
Italy	5194	870	375	75	Africa	2248	1451	97	56
Japan	8154	2101	603	153	Other Asia	2454	2237	114	103
United Kingdom	5809	1362	464	150	Eurasia	2387	1998	105	69
United States	4587	1549	197	81	Europe	2361	1950	104	72
					North America	2362	1640	86	48
					Oceania	3436	1638	113	55
					South America	2595	1529	99	49

3.1. *Systemization of investment costs assumptions (CAPEX)*

In this subsection, we are going to explore CAPEX assumptions of solar PV, CSP, onshore, and offshore wind from reviewed studies compared with the reference values.

For solar PV, most studies assume an average CAPEX between 1000 and 2000 $/kW for 2020 (see Fig. 1). However, in some countries, the CAPEX for solar PV is lower already today (see Table 2), for example, in India with 800 $/kW. The reference source (REF1) shows that the global average investment costs have fallen rapidly in the past ten years and are already at 1210 $/kW by 2018. However, the slope of the reviewed scenarios does not seem to reflect the historical cost reduction trend. About half of the scenarios considered are above the actual reference value from 2018, and almost all scenarios see a rather low absolute cost reduction potential after 2020. After 2020, 100% Jac. reported the highest average CAPEX for solar PV at around 2000 $/kW with little reduction potentials, while E[R] Brazil assumes a much steeper reduction potential (although with a higher assumption for the base year). The assumed costs in both LUT studies are the lowest and reach a value of about 300 $/kW in 2050. The WEO assumed scenario-specific costs. In their NP′18 scenario, they reduced their cost assumptions by around 300 $/kW for the year 2020 compared to the scenarios published in 2017. Overall, the average cost assumptions for photovoltaics range from about 300 $/kW to 1600 $/kW in 2050, i.e. they diverge by a factor of more than 5.

Only IESS, 100% Jac. and WEO studies reported cost ranges for solar PV. However, the lower bound cost assumptions of these studies are still all above the cost assumptions of LUT and CREO. It is interesting to observe that many of these studies do agree on the future costs of PV and are near the values of the WEO NP′18 scenario. On Fig. 1, this can be read from the dark grey areas that result from the superposition of many different studies.

For CSP, the average investment cost assumptions in the reviewed studies also show a large divergence, even at the beginning of the observation period (see Fig. 2). This is probably due to different assumptions about system configurations (e.g. whether, how much, and what kind of storage are included in the cost assumptions, more detail is given in Table 3 in chapter 4). Before 2013, all the CSP projects (covered by the historical IRENA database) referred to the technology of parabolic trough with or without storage. Since 2014, new technologies such as linear Fresnel and solar towers have been coming into the market, contributing to the fluctuations in costs (5,000–10,000 $/kW). In addition, today's CSP deployment is still relatively low, and therefore the projections vary more strongly. For example, CREO and E[R] Brazil assume a fast costs decline for 2020 and 2030, while others assume only a slight decline (or no decline at all). Similar to solar PV, the spread of

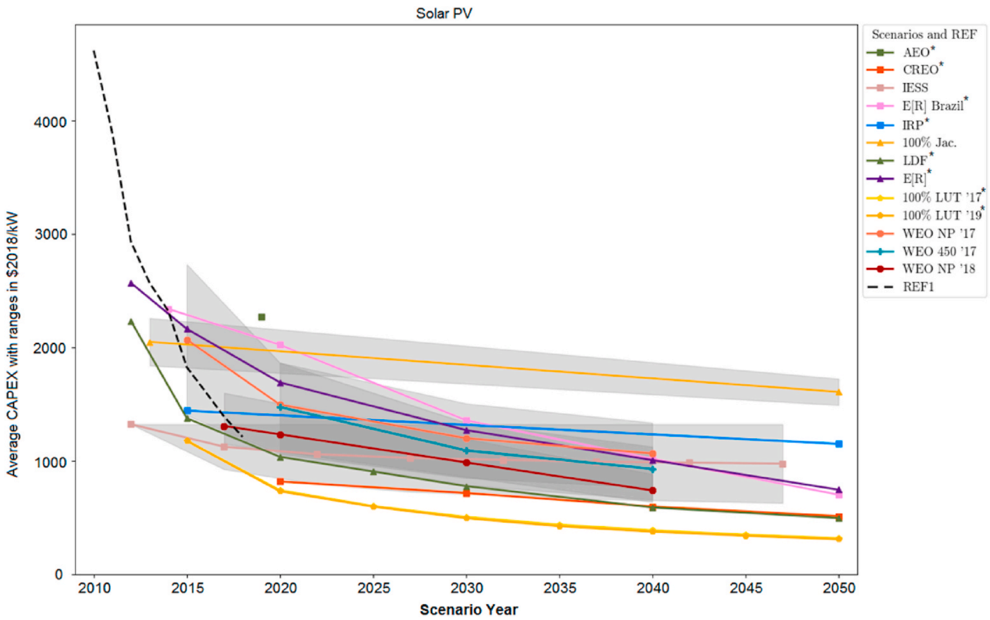

Fig. 1. Comparison of average CAPEX represented by solid lines with assumption ranges (in grey) when available of reviewed scenario studies for PV (* represents that there is no costs ranges available, the same below).

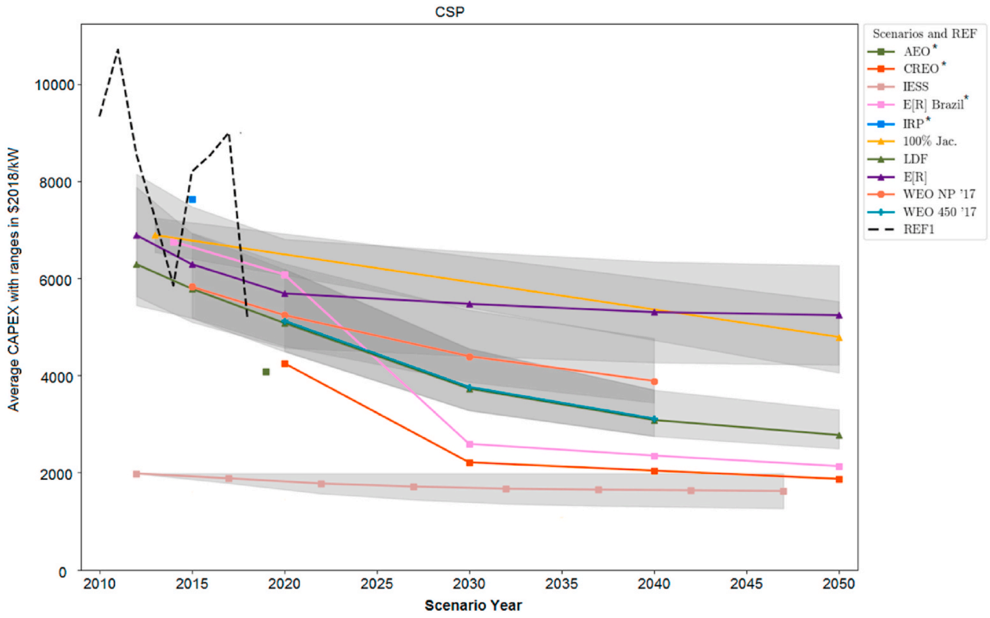

Fig. 2. Comparison of average CAPEX with assumption ranges when available of reviewed scenario studies for CSP.

the average costs assumptions for 2050 shows a factor of 6.

The other five studies consider significantly different costs ranges for CSP (IESS, 100% Jac., LDF, E[R], WEO). Their ranges before 2020 are in line with the current market auctions. The only exception is IESS with much lower values. For CSP, there is very little overlap, which means that the cost assumptions form the different studies do not agree.

Quite different from the solar costs, the assumptions for onshore wind costs show a divergence to remain essentially constant over time (see Fig. 3). Most studies see a little potential for its cost decline. As Table 2 indicates, the costs of onshore wind can be regionally different (for example much higher costs are currently observed in Europe, Brazil and North America, while it is quite the opposite in China and India), which explains some outliers in costs assumptions. It is surprising that there are five studies that assume costs over the whole period that are higher than those observed in 2018. The assumptions of IESS are on the other extreme, being close to 1000 $/kW over the whole period. The assumed costs for E[R] Brazil are also lower than market costs. WEO has largely reduced its cost assumptions in its 2018 study (compared to the 2017 study), which is now in line with the current values from IRENA. The spread of the average cost assumptions for 2050 is less than a factor of two, with ranges between 1000 and 1700 $/kW.

However, the assumptions for the cost ranges of onshore wind are much broader than those for solar PV, especially for the WEO studies, where different region-specific costs are assumed. Except for IESS, even the lowest assumptions in 2040 or 2050 are similar to the current costs in China and India (Table 2). For onshore wind, we can see that the studies agree on cost ranges between 1300 and 1700 $/kW for all years with a slightly decreasing trend.

In terms of offshore wind, most studies assumed costs close to market values, except IESS and CREO with assumptions lower than 3000 $/kW (see Fig. 4). Contrary to onshore wind, most studies see a large cost reduction potential, even though a clear trend cannot yet be inferred from the market (REF1). There is a three-fold difference in cost assumptions for 2050 between the lowest (CREO) and highest estimates (100% Jac.) with a gap of around 2000 $/kW. Many studies do agree on the future costs of offshore wind (dark grey areas in Fig. 4). Only IESS and CREO use significantly lower costs.

3.2. *Systemization of levelized cost of electricity (LCOE) assumptions*

In this subsection, we are going to compare the LCOE assumptions of solar PV, CSP, onshore, and offshore wind from reviewed studies with from auctions. Similar to section 3.1, the country or region-specific data are available for PV and onshore wind (but not for CSP and offshore wind) as shown in Table 2, and therefore are also part of the analysis (but not shown in the figures).

First, note in Fig. 5 that in the last years, solar PV values from REF1 are similar as in REF2, as to be expected. The difference in earlier years (2010–2014) is due to the fact that the auctions (of REF2) did not correspond to a global average, but to a selection of particularly sunny countries that used tenders from very early on.

All studies show a decrease in LCOE of solar PV, but at a much slower rate than in the auctions. Only one study (E[R]) assumes cost for 2050 below today's auction's value. In other words, planning agencies use costs for 2050 that have been invalidated in today's market. The huge difference on average costs across the scenarios (e.g. in 2020 ranging from 80 to 200 $/MWh or in 2050 ranging from 50 to 120 $/MWh) does not improve the situation. Nor does the fact that many studies agree on the LCOE from 2020 onwards (dark grey area).

All studies except for IRP reported LCOE cost ranges for solar PV. It shows a narrowing divergence towards 2050, with only half of the range-magnitude of 2020. However, even the inferior bounds of 2040 or 2050 are only a little lower than the market auctions in 2018.

The majority of the studies project a relatively limited cost reduction potential for CSP since 2020 (except EU), albeit from having completely different starting points (see Fig. 6). The current and anticipated cost reduction inferred from the auctions is not anticipated by any study. All of them assume costs for 2050 to be higher than the current auction price (70 $/MWh by 2021). This picture does not change when lower bound assumptions are considered.

The majority of the studies show a limited potential for average onshore wind costs reduction, except EU and AIM/CGE (see Fig. 7). This is comparable to our observations in section 3.1. Most of the cost assumptions tend to be in the range of today's values between 50 and 100 $/MWh, but the current reduction trend is not considered by any study in this form. Especially in the EU-study the average LCOE costs are quite high compared to the current weighted average values in Europe (Table 2). Besides, AEO also assumed much higher LCOE than the current reference values in North America for all the scenario years. However, only MESSAGE considers the assumptions that are lower than the current global weighted market auctions (both for the upper and lower bounds).

Table 3
Further information on reviewed energy scenario studies.

Study abbreviation	LCOE data		CAPEX data		O&M assumptions data available?	Type of discount rate (private or social)	Sensitivity of renewable technology costs?	Information on used cost forecast method	Note
	Available?	With ranges?	Available?	With ranges?					
AEO	✓	✓	✓	×	✓	Private (uniform for all techs)	×	×	
CREO	×	×	✓	×	✓	×	×	×	
EU	✓	✓	×	×	×	Private (varies across sectors with the consideration of risk)	×	Learning curves specific to each technology	
IESS	✓	×	✓	✓	✓	×	✓	×	
E[R] Brazil	✓	×	✓	×	✓	Private (uniform for all techs and regions)	×	×	
IRP	✓	✓	✓	×	✓	Private (uniform for all techs)	×	Assumed technological specific future learning rates	The authors do not provide share for the technologies in the final results. Thus, equal weighted averages are assumed.
100% Jac.	✓	✓	✓	✓	✓	Social	✓	×	The authors provide specific assumptions on the share of the technology type for PV and CSP which is considered in the calculation.
LDF	✓	×	✓	✓	✓	Private (uniform for all techs and regions)	×	×	
E[R]	✓	✓	✓	✓	✓	Private (uniform for all techs and regions)	×	×	
100% LUT '17	×	×	✓	×	✓	Private (uniform for all techs)	×	×	For PV, average weighted costs assumptions by installed capacities of each technology for our analysis. The CAPEX for thermal energy storage of CSP is unknown and therefore could not be part of the comparison.
100% LUT '19	×	×	✓	×	✓		×	×	
WEO NP '17	✓	×	✓	✓	✓	Private (uniform for all techs and regions)	×	Assumed technological specific future learning rates	
WEO 450 '17	×	×	✓	✓	✓		×		
WEO NP '18	✓	✓	✓	✓	✓		×	Assumed technological specific future learning rates	Value-adjusted LCOE to combine LCOE with simulated energy value, flexibility value and capacity value by technology
AIM/CGE	✓	×	×	×	×	Private (uniform for all regions and actors)	✓	×	
IMAGE	✓	✓	×	×	×		✓	×	
MESSAGE	✓	✓	×	×	×		✓	×	
POLES	✓	✓	×	×	×		✓	×	
REMIND	✓	✓	×	×	×		✓	×	
WITCH	✓	✓	×	×	×		✓	×	
REF 1	×	×	✓	×	✓	Private (varies across those regions with no consideration of financial support)	×	×	Average values used
REF 2	✓	×	×	×	×		×	×	

In line with our observations on offshore wind in section 3.1., the current reference values for the offshore wind also appear to be subject to great uncertainty (see Fig. 8). In the auction data, a sharp fall in prices is emerging, which was not anticipated virtually by any study. Most of the cost assumptions tend to be in the range of today's values. MESSAGE is on the other extreme: it assumes values much lower than those observed today with hardly any further changes towards 2050. All studies except for EU reported LCOE costs ranges for offshore wind. These ranges are broader than those for onshore wind, with almost no agreement towards 2050. Only in E[R] (lower bound only), WITCH (lower bound only) and MESSAGE are below the current market auction values for the year of 2022. Quite different from other technologies, there is little overlap on the assumed LCOE of offshore wind.

4. Discussion

Energy scenarios in the past have consistently underestimated the uptake of renewable energy technologies [8,9]. This motivated our analysis under the hypothesis that the cost assumptions in energy scenario may be systematically overestimated. Our results show that this

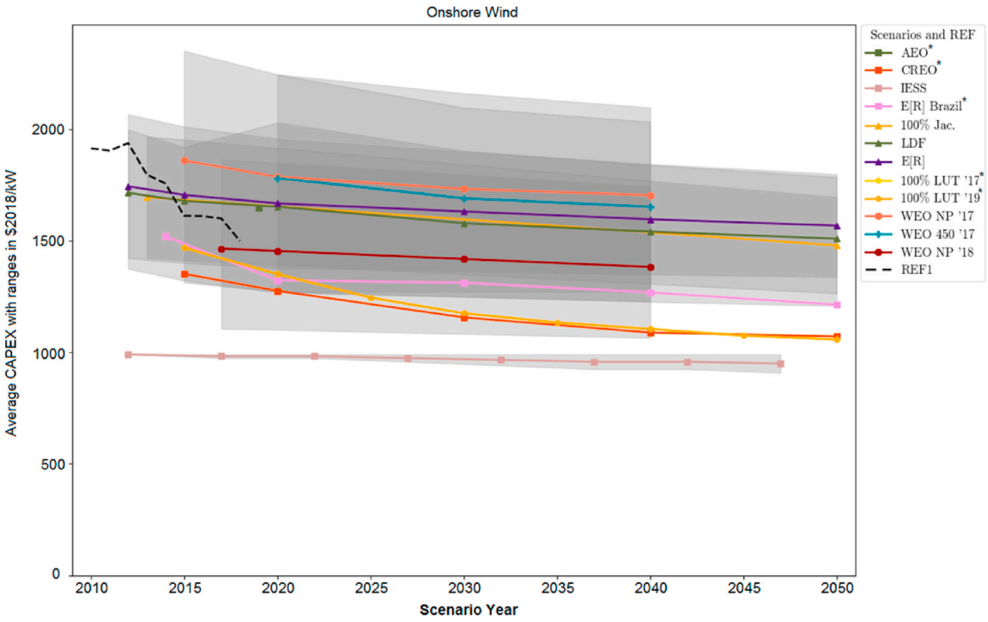

Fig. 3. Comparison of average CAPEX with assumption ranges when available of reviewed scenario studies for onshore wind.

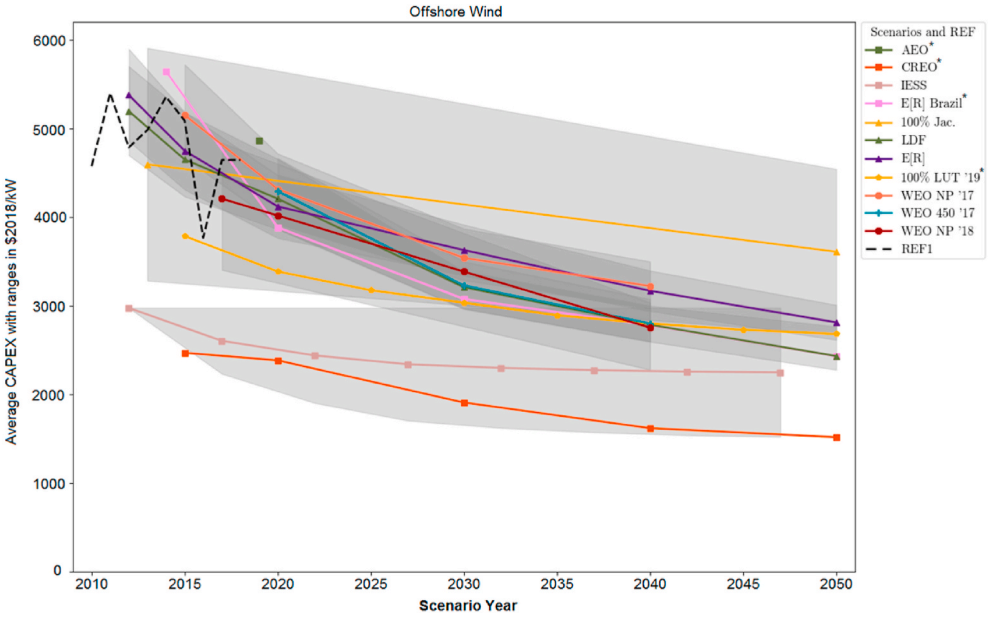

Fig. 4. Comparison of average CAPEX with assumption ranges when available of reviewed scenario studies for offshore wind.

statement does hold true for many cases, but not for all.

In the following, possible reasons for the gap between the costs observed in the markets (reference scenario) and energy scenario assumptions are discussed. We start discussing how the current costs assumptions misalign with market costs (CAPEX in section 4.1 and LCOE in section 4.2) as a direct response to our previous sections (3.1 and 3.2). We then explore a series of factors that might explain the found misalignments between cost assumptions and observed costs, starting with discounting assumptions (section 4.3), cost-forecast methods (section 4.4), market distortions (section 4.5), and access to up-to-date data and status-quo bias (both in section 4.6). The overview of the underlying assumptions of the reviewed studies, i.e. LCOE, CAPEX and O&M data, discount rate, sensitivity analysis on renewable technology costs, and applied methods for cost-forecast are shown in Table 3. Discount rates are assumed to be private unless otherwise stated in the studies.

4.1. *Investment assumptions misaligned with market costs*

A relatively consistent picture is presented concerning CAPEX: our analysis shows that the historical trend in cost decrease of renewable technologies is not reflected in future energy scenarios. In other words, most studies overestimate future costs of renewables. A particularly dramatic case is solar PV, where observed costs for 2019 are lower than many assumptions used in energy scenarios for 2050. The studies with lower (and thus more correct) cost assumptions, were subject to strong criticism in the past (see e.g. Refs. [8,9]).

More recent studies do a better job of reflecting cost developments. In particular, the studies of WEO ′18 and LDF 2019 have made strong adjustments in comparison to previous analyzes from the same institutions (WEO ′17 and Energy [R]evolution 2015). For example, the CAPEX assumptions for PV in 2020 have been reduced by around 700

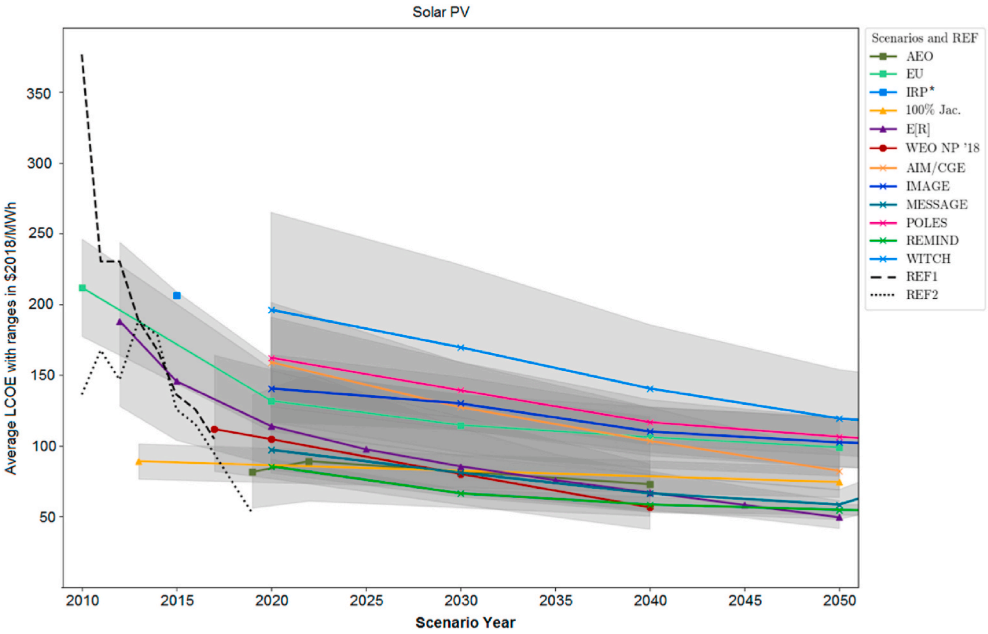

Fig. 5. Comparison of average LCOE with assumption ranges when available of reviewed scenario studies for PV.

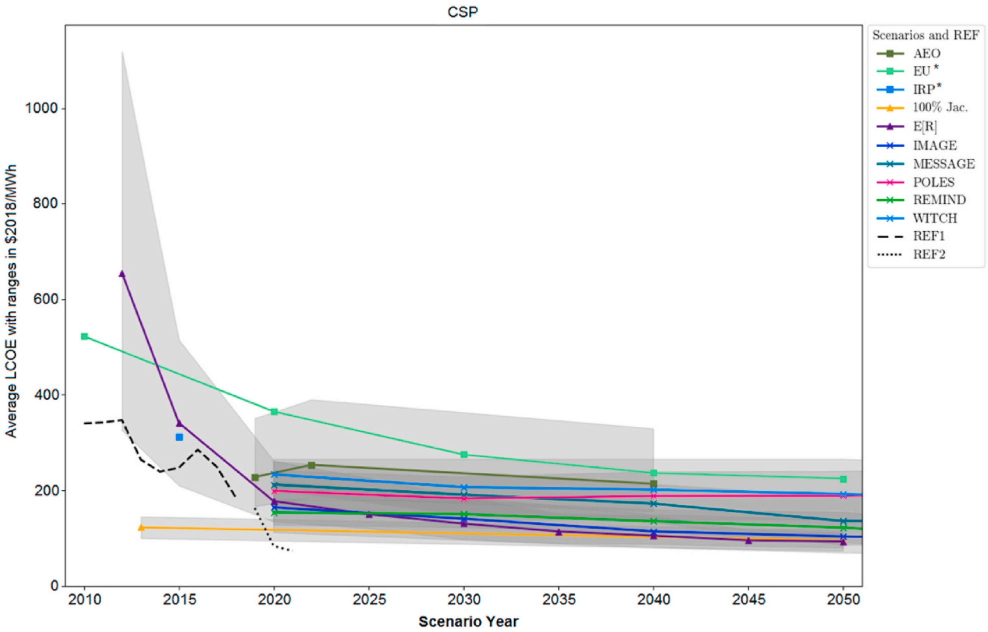

Fig. 6. Comparison of average LCOE with assumption ranges when available of reviewed scenario studies for CSP.

$/kW (by comparing [2,5]); the CAPEX assumptions for onshore wind in 2020 have been reduced by around 300 $/kW (by comparing [21,22]), which reflects the current global average reduction trend according to Ref. [17].

Only a couple of studies underestimate future costs. For example, CREO [27] and IESS [23] use offshore wind costs starting in 2015 that are well below the market prices observed today in 2020. This might be caused by the inherently higher uncertainty about cost estimates for emerging technologies, especially when these show considerable regional differences in installation cost. However, the many system components and designs of this technology (e.g. type and capacity of storage) in the reporting created confusion may have lead to an incorrect estimation of the costs.

In short, energy scenarios have ignored current costs developments to a large extent, especially for the rapid price decline of PV and arguably CSP.

4.2. *Levelized costs of energy assumptions misaligned with market auctions*

We found that not even the lowest LCOEs assumptions (in the investigated studies) capture current nor near-future market expectations (measured by auctions results). Virtually all consulted studies hugely overestimate the costs. In the extreme, assumed costs for 2050 are higher than observed costs for 2019. Solar PV, CSP, and offshore wind seem particularly plagued by this situation. Cost assumptions for onshore wind seem marginally better, with some scenarios (on price sensitivities) following the current cost data, and with one study even

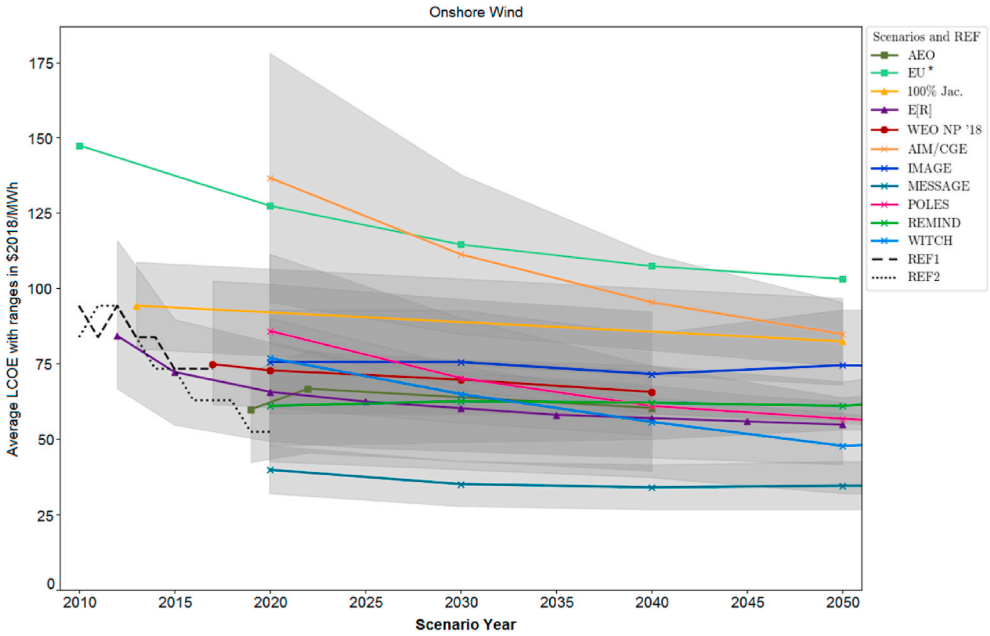

Fig. 7. Comparison of average LCOE with assumption ranges when available of reviewed scenario studies for onshore wind.

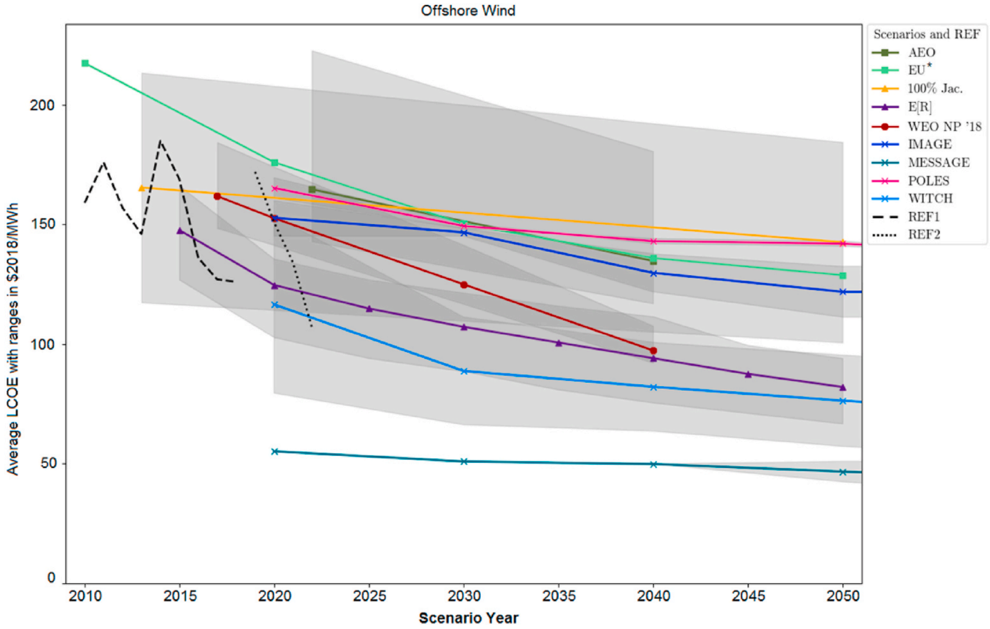

Fig. 8. Comparison of average LCOE with assumption ranges when available of reviewed scenario studies for offshore wind.

underestimating the costs. Moreover, almost all studies project a certain “leveling off” in cost decrease, whereas “real-world” market data does not support this claim, at least not yet.

Now, correctly estimating LCOE is more complex when compared to simple capital cost assumptions (addressed in the previous subsection), because of its many other underlying factors. These include, for example, increasing capacity factors [16] and lifetimes, decreasing degradations [34], higher efficiencies and thus higher energy output, and lower capital costs. Indeed, the substantial differences between CAPEX and LCOE show that the asserted scenario inconsistencies stem less from direct technology costs, but more assumptions inherent to LCOE [35]. The capital cost is one of the main drivers, which we will discuss in the following subsection.

4.3. *Discounting assumptions*

Higher discount rates make levelized electricity provision more expensive for all energy technologies, but more so for low-carbon technologies, which are capital-intensive. Higher discount rates, therefore, put RET in a comparatively worse position, while lower rates benefit RET disproportionately [36]. A large part of the levelized cost reduction in RET can, therefore, be explained by the worldwide low discount rates of recent years. The latter was shown, by Egli et al. [37]. They state that the (LCOE) cost reduction of onshore wind and solar PV between the beginning of the century and today can be attributed by 40% to changes in financing costs.

Using capital costs specific to each region is rarely done (recall Table 3), although they vary widely and might suffer from distortions.

For example, for reducing the risk for investors and borrowers feed-in tariffs, governmental loan programs (such as India's loan program for solar home systems with rates of about 5%), or green bonds (such as China's Green Bond Directives and a Green Bond Catalogue) are often in place but not captured in energy scenario models [38]. On the other hand, the significantly higher cost of capital in countries like Brazil (28%) or Madagascar (29%) are also not considered [39]. However, capturing the changing financing properties and the general level of discount rates is pivotal for assessing future technology [36,37]. From our analyzed studies, only Ref. EU took a private discount rate that varies across sectors of energy supply, firms, and individuals of energy demand to capture sector-specific risk. And in terms of what kind of discount rate is used, only the study of 100% Jac [31]. takes a social discount rate, which tends to underestimate the intensity of policies that may enable the transition [28] into account.

RET can also be financed with higher leverage with increasing technological and regulatory maturity. In other words, the proportion of comparatively more favorable debt capital in project financing can be set higher. Also, an overall "experience effect" in granting loans for RET (due to greater competition and generally lower anticipated project risk) reflects in lower discount rates [37].

4.4. *Costs forecast methods*

There are different methods for forecasting costs of renewable technologies. These include bottom-up technology-based analyses of the cost reduction potential along the manufacturing value chain [18], expert elicitation studies for future energy costs of wind [40] and PV [41], and learning curves [42–47]. From the 21 studies evaluated, only 4 informed their cost-forecasting methods (recall Table 3). All of them used learning curves ([21,22,28,30]).

Considering learning curves for costs is important to influence the competitiveness of technologies by timing investments to earlier planning years [48]. This is an active maturation of technologies, such as Germany did with the feed-in tariff for PV in the early 2000s. Conversely, neglecting cost reduction potentials could result in a failure of emerging technology start-ups and public policy programs (e.g. for wind [49], for solar energy [9,50,51]; for storage technologies [52–55]).

Studies also suggest that other approaches might be more precise: focusing on technological details first, followed by non-aggregated and systemic cost estimates while keeping the experts aware of any discrepancies, should they arise [43,56–58].

Note that cost reductions may not continue indefinitely and that well-behaved learning curves do not necessarily exist for every product or technology [59,60] (although they do exist for many). Ideally, the estimation of technology learning rates should consider uncertainty and risk, but this is often hindered by the computationally expensive optimization tools [61–63].

4.5. *Market distortions*

Access to real-market cost information is a central proxy in this study to interpret the expectation for future market developments (especially for still rather immature low-carbon technologies, like shown here CSP and offshore wind). The question still remains whether auctions can reveal "real-world" costs. It may be that current auctions are subject to a *winners curse*, speculation, portfolio management, or strategic bidding to secure certain (future) market shares. For example, the competitive pressure may provoke auction bids to be just enough to ensure debt coverage, but with little to no profits for the developer. If so, this would be revealed in the mid-term. Now, even if the actual LCOEs are slightly higher than those reported by the auctions, this cannot hide that most studies seem to systematically and significantly overestimate technology costs, especially for solar PV, CSP, and offshore wind, and that most studies underestimate the efficiency improvement and cost reduction the market is capable of delivering.

For effective policy design, energy scenarios should be capable of testing key assumptions and of exploring the possibility space of energy futures much more thoroughly [64]. Even "extreme" perspectives are useful in this context. With easy-amendable and community-wide data access, the ranges of input drivers, such as cost assumptions, could be systematically expanded. Currently, we believe that not all modelers do so, and a retrospective analysis found that scenario choices reflected contemporary debates [65]. It should be food for thought that just the "extreme" RET deployment scenarios correlate well with the actual development of RET (see e.g. Ref. [9]).

4.6. *Access to up-to-date data and status-quo bias*

Cost assumptions are often poorly documented and, therefore, non-transparent for other modelers [66]. We experienced this first hand when researching for the assumptions in the evaluated studies, which sometimes could not be reliably extracted. Due to this reason, some relevant energy scenarios had to be excluded from this study. Moreover, central financial assumptions like discount rates and O&M costs were mostly unavailable and, thus, not systemized in our work. Furthermore, flexibility options such as storage, transmission grids, and sector coupling are essential for energy systems with high shares of renewables. In this area, the cost assumptions are even less transparent and comparable (and, therefore, also not part of our quantitative analysis). Energy system modelers and scenario developers should aim to make their studies transparent and accessible to avoid unnecessary frictions.

Currently, there is a strong movement to make energy scenarios and models more open and transparent [67–69]; this momentum could be used in the realm of cost data. Since the RET industry is shifting rapidly, this work makes a strong case that it should become standard to update cost assumptions on a regular basis and specify the assumptions for regions or countries. An open-access, up-to-date cost database would help the community greatly to adapt their assumptions more quickly. One major obstacle in this direction is that economic data is often sensitive for stakeholders involved (e.g. rates, leverages, costs for buying technology, manufacturing cost, etc.). As a first step, the data collected in this review are made publicly available (see Ref. [25]). We also propose the community to develop a standardized data structure to facilitate model exchange.

The inherent time lag between data research, model construction, review, and publication supports a status-quo bias. This bias might be partially responsible for inconsistencies. Scenario developers and modelers should work on new forms of publications that can be adapted and amended to new market situations in a fast-changing world. Another contributing factor to the status-quo bias, that prevents researchers from taking more progressive cost estimates, is a certain precautious attitude towards the review process. From open review processes, it can be seen how reviewers criticize or object studies with "very low" or seemingly "unrealistic" cost estimations. Recalling the broad cost assumptions shown in our figures, it is no wonder that researchers and reviewers (and policymakers and the general public) cannot keep up with the rapidly declining cost of renewables and might draw biased conclusions.

5. Conclusions

In our analysis, we analyzed the cost assumptions used in scenario studies. We looked at the averages and ranges (when available) of levelized costs of energy (LCOE) and investment costs and compared them to recent auction prices and investment costs from the International Renewable Energy Agency [17], respectively.

Results show extremely high differences in cost assumptions between the studies. In terms of investment costs by 2050, the scenarios differ by over a factor of five for solar photovoltaic (PV), around six for concentrated solar power (CSP), two for onshore wind, and three for offshore wind. In terms of levelized costs of energy for solar photovoltaic, only one study (E[R]) assumes that the cost in 2050 will be below today's auctions values. In other words, planning agencies use costs of PV for 2050 that have been invalidated in today's market. For concentrated solar power, this is even more extreme: all study use costs assumptions for 2050 that are higher than the current auction prices (70 2018$/MWh by 2022). The cost assumptions of onshore wind for 2050 tend to be in the range of today's values between 50 and 100 $/MWh; further reductions are not considered by the studies.

This abovementioned overestimation of costs of renewable energy technologies in model-based energy scenarios can result in several systematic distortions with substantial consequences:

- The economic potential of renewable technologies is underestimated.
- The transformation and mitigation costs are overestimated.
- In the worst case, transformation efforts towards clean energy are delayed, in the false belief that they are too expensive that may lead to misadjusted incentive systems.

The found differences between the values from energy auctions and the global levelized costs of energy could be explained as follows. Differences in auction specifications, local regulations, economic and strategic circumstances of the bidders, capacity factors, and plant size result in variances in bidding prices [70]. Also, due to potential competitiveness among bidders with access to the best locations for construction, the project-based auction prices could be lower than the system-wide cost averages. Moreover, the auctioned projects are implemented with a certain time lag; to a certain extent the auctions reflect only the market expectation of (and the not necessarily yet realized) cost developments in the near future. But, in our analysis for CSP and offshore wind, we looked at regional averages due to unavailability of more specific auction prices data. Thus, follow-up studies should investigate in more detail the regional dependence of the discrepancy between scenario cost assumptions and actual values. One should also investigate the cost assumptions of other technologies such as carbon capture and storage (CCS), hydrogen, biofuels, etc.

Finally, researchers should also update assumptions on economic lifetimes, full-load hours, systems' degradation, and operation and maintenance costs. The "Tracking the Sun" initiative [71] could serve as a role model for comprehensive and up-to-date cost data reporting. Furthermore, the scenario community should aim to understand and pay more attention to the rapidly declining cost of renewable energy technologies, since this aspect has a decisive impact on the results of model-based energy scenarios. Some scholars have argued that modular renewable energy technologies show cost decreases following an exponential curve rather than a power-law-experience curve, making the "leveling-off" of cost decrease much less pronounced [72]. These claims deserve more attention, and they should be tested more often in "edge case" energy scenarios.

Authors' contributions

Mengzhu Xiao: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – review & editing, Visualization. Tobias Junne: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – review & editing, Visualization. Jannik Haas: Formal analysis, Writing – review & editing, Visualization. Martin Klein: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization.

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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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