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Review Article

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ABSTRACT

Recent global events emphasize the importance of a reliable energy supply. One way to increase energy supply security is through decentralized off-grid renewable energy systems, for which a growing number of case studies are researched. This review gives a global overview of the levelized cost of electricity (LCOE) for these autonomous energy systems, which range from 0.03 $\$_{2021}$/kWh to over 1.00 $\$_{2021}$/kWh worldwide. The average LCOEs for 100% renewable energy systems have decreased by 9% annually between 2016 and 2021 from 0.54 $\$_{2021}$/kWh to 0.29 $\$_{2021}$/kWh, most likely due to cost reductions in renewable energy and storage technologies. This review identifies and discusses seven key reasons why LCOEs are frequently overestimated or underestimated in research, and how this can be prevented in the future. This overview can be employed to verify findings on off-grid systems, to assess where these systems might be deployed and how costs evolve.

1. Introduction

Recent events have reduced the otherwise steadily increasing annual percentage of the global population with access to electricity for the first time in years [1]. Due to long distances to grid infrastructure, off-grid renewable energy systems are economically viable options to provide larger electricity access in developing regions like sub-Saharan Africa [2–4]. Even in industrialized countries with nationwide electrification, many local communities are striving for autonomous energy systems with 100% renewable energies [5–7], often motivated by economic, environmental and/or social reasons [8]. Decreasing costs for renewable energy technologies [9,10] as well as current cost uncertainties relating to supply from centralized infrastructures [11] will probably further increase the economic incentives for energy autonomy.

For several years the feasibility of 100% renewable energy systems has been controversially discussed [12–14] and there have been some insights into how these systems could be implemented [15–17]. Existing reviews also highlight regulatory issues, such as greater utilization of centralized infrastructure by energy autonomous communities [18,19]. Other relevant studies include recent bibliometric analyses of 100% renewable energy systems [20], comprehensive reviews of the history and future of 100% renewable energy systems [21], reviews of 100% renewable energy scenarios on islands [22], and reviews of best practices and potential improvements for modeling such energy systems [2]. While the majority of these studies focusses on national energy systems, the latter two studies partly address the levelized cost of electricity (LCOEs) for decentralized energy systems. In Meschede et al. [22] this is only dealt with sporadically, whereas Weinand et al. [2] analyze the LCOEs for decentralized autonomous energy systems in a more detailed way. However, since the publication of the latter study, the number of studies on decentralized energy autonomy has increased considerably (see Section 2) and the costs are not discussed in detail because the study focuses more on modeling aspects. Therefore, this systematic review intends to answer the following research questions:

- How have the costs for decentralized energy autonomous systems developed in recent years?
- Have previous studies overestimated or underestimated the LCOEs?
- What are the reasons for overestimation and underestimation of LCOEs?

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Abbreviation

Description	
CO_2	Carbon dioxide
CuCoPy	Currency Conversion for Python
HOMER	Hybrid Optimization of Multiple Energy Resources
IRENA	International Renewable Energy Agency
IREOM	Integrated Renewable Energy Optimization Model
ISLA	Island System $LCOE_{min}$ Algorithm
LCOE	Levelized cost of electricity
LINGO	Optimization Modeling Software for Linear, Nonlinear, and Integer Programming
NREL	National Renewable Energy Laboratory
PV	Photovoltaics
RE	Renewable Energy
RE^3ASON	Renewable Energies and Energy Efficiency Analysis and System Optimization

2. Methods

Definition of off-grid renewable energy systems. In this study, off-grid renewable energy systems are defined as systems in which both electricity as well as heating and cooling demands are met by renewable energy. As shown in the subsequent results section, the review focuses on systems with 100% renewable energy but also discusses off-grid systems that import fossil fuels and use them in diesel generators. While most of the case studies in this review are disconnected from the grid, we also include a few outliers that rely on backup capacity from the overlaying grid. In the latter cases, however, more than 100% of annual energy demand is provided by renewable sources in all of the regions considered.

Literature search. With a specific search query in the literature database Scopus[1] [23], 730 studies between 1990 and 2021 have been found. For energy autonomy, many different terms are used in research studies, which are supposed to be covered as completely as possible by the search query. Nevertheless, some uncertainty remains, that not all relevant studies are included by the search query. Through a manual check of titles, abstracts and full texts of the 730 studies, 228 articles were identified that address decentralized energy autonomy in small regions such as villages, municipalities, islands, or cities. This number of articles nearly doubled between 2020 and 2021 with 105 new studies in this period. 161 of the 228 articles [24–184] specify LCOEs for autonomous energy systems (see Fig. 1), of which 83 studies were published until 2019 and were previously identified by Weinand et al. [2]. Energy system analyses for individual residential, commercial, or industrial buildings/applications as well as analyses of large regions such as federal states, entire countries, or continents were excluded here. All economic cost values stated in this review are inflation adjusted and refer to the year 2021. Furthermore, studies with LCOEs above 1 $\$_{2021}$/kWh are excluded in the following analysis (see explanations in Section 3.1).

[1] Search query taken from Weinand et al. [2]: TITLE-ABS-KEY ("energy system" AND ("simulation" OR "modeling" OR "optimization" OR "analysis") AND ("region" OR "municipalities" OR "municipality" OR "communities" OR "community" OR ("district" AND NOT "district heating") OR "city" OR "cities" OR "town" OR "remote") AND ("off-grid" OR "off grid" OR ("100%" AND "RE") OR ("100%" AND "renewable") OR ″100%-renewable" OR ("energy" AND "autonomy") OR ("energy" AND "autarky") OR ("energy" AND "self--sufficiency") OR ("energy" AND "self-sufficient") OR "energy independent" OR "stand-alone" OR "energy autonomous" OR "island system")) AND (LIMIT-TO (DOCTYPE,"ar")) AND (LIMIT-TO (LANGUAGE, "English")).

3. Results

The inflation-adjusted LCOEs in Fig. 1 calculated by the 161 case studies range from 0.03 $\$_{2021}$/kWh in Alotaibi & Eltarnaly [38] (Saudi-Arabia) to 0.99 $\$_{2021}$/kWh in Rehman et al. [163] (Pakistan), with a total mean value of about 0.35 $\$_{2021}$/kWh (median is 0.29 $\$_{2021}$/kWh and mode is 0.24 $\$_{2021}$/kWh). Since 2016, the mean LCOEs for autonomous energy systems have decreased from 0.33 $\$_{2021}$/kWh (<100% renewable, i.e., including fossil fuels) and 0.54 $\$_{2021}$/kWh (100% renewable) on average by 4% and 9% per year to 0.23 $\$_{2021}$/kWh and 0.29 $\$_{2021}$/kWh in 2021, respectively. In all articles that consider both hybrid renewable-fossil-fuel systems and 100% renewable systems, the latter are on average 24% more costly. However, all hybrid systems include large shares of renewables and due to the stronger cost degression for 100% renewable systems, the cost deviation could progressively diminish.

Most studies in the research field of energy system analysis originate from the United States of America, China, United Kingdom, Germany and Italy [189], however, most of these countries are underrepresented in the 161 case studies on off-grid systems. Among the case studies that explicitly mention LCOEs, most were conducted for India (22%), Iran (7%), China (7%), Nigeria (5%) and Canada (4%). While 3% of the studies were conducted for German and 1% for Italian regions, no case studies were published for the United States of America or the United Kingdom. In some countries such as Spain [91], Germany [136] and New Zealand [139] with comparatively high electricity prices (cf. Fig. 1), the calculated LCOEs for off-grid systems are partly below the household electricity prices (which also contain taxes and levies) in December 2021 of 0.32 $\$_{2021}$/kWh, 0.34 $\$_{2021}$/kWh and 0.19 $\$_{2021}$/kWh, respectively [188].

Of the 161 case studies, 100 consider 100% renewable energy systems without fossil fuels. The majority of these studies (63%) applied the HOMER (Hybrid Optimization of Multiple Energy Resources) or HOMER Pro simulation models. The HOMER model is a widely used open-source software tool for designing microgrid systems. Developed by the National Renewable Energy Laboratory (NREL), it is used to evaluate the technical and economic feasibility of integrating different energy sources, such as solar, wind, and energy storage, into a microgrid. The model considers inputs such as weather, load profiles, and equipment performance to determine the optimal configuration of a microgrid system. Other studies used the optimization models RE^3ASON [179,180], Off-gridders [60], LINGO [103], ISLA [145] and IREOM [104], the simulation models H_2RES [114], and EnergyPLAN [74] or metaheuristics like particle swarm optimization [97,117,153,161], genetic algorithms [98,117,142,156] or discrete harmony search [64]. Furthermore, Kumar & Saini [117] compare nine different metaheuristics for the energy system optimization of five un-electrified villages in India and demonstrate that the Salp Swarm Algorithm converges most efficiently.

While most studies consider off-grid systems and thus complete energy autonomy, this study also includes five case studies with balanced autonomy. The latter means that although significantly more energy is provided annually by local renewable energy sources than is required in the region, backup capacity is also available through the overlying grid. These studies only involve analyses in industrialized countries, namely Canada (Bagheri et al. [51,52]), Croatia (Krajačić et al. [114] and Dorotić et al. [74]) and Germany (Kötter et al. [113]). In addition, most case studies focus on meeting electricity demand, while the minority also consider heating and cooling requirements (e.g., Akthari & Baneshi [32] or Weinand et al. [179,180]).

The following sections analyze why some studies overestimate (Section 3.1) or underestimate (Section 3.2) the costs of 100% renewable off-grid energy systems and how this could be improved in the future. Thereby, the focus lies on the 100 case studies with 100% renewable energy systems.

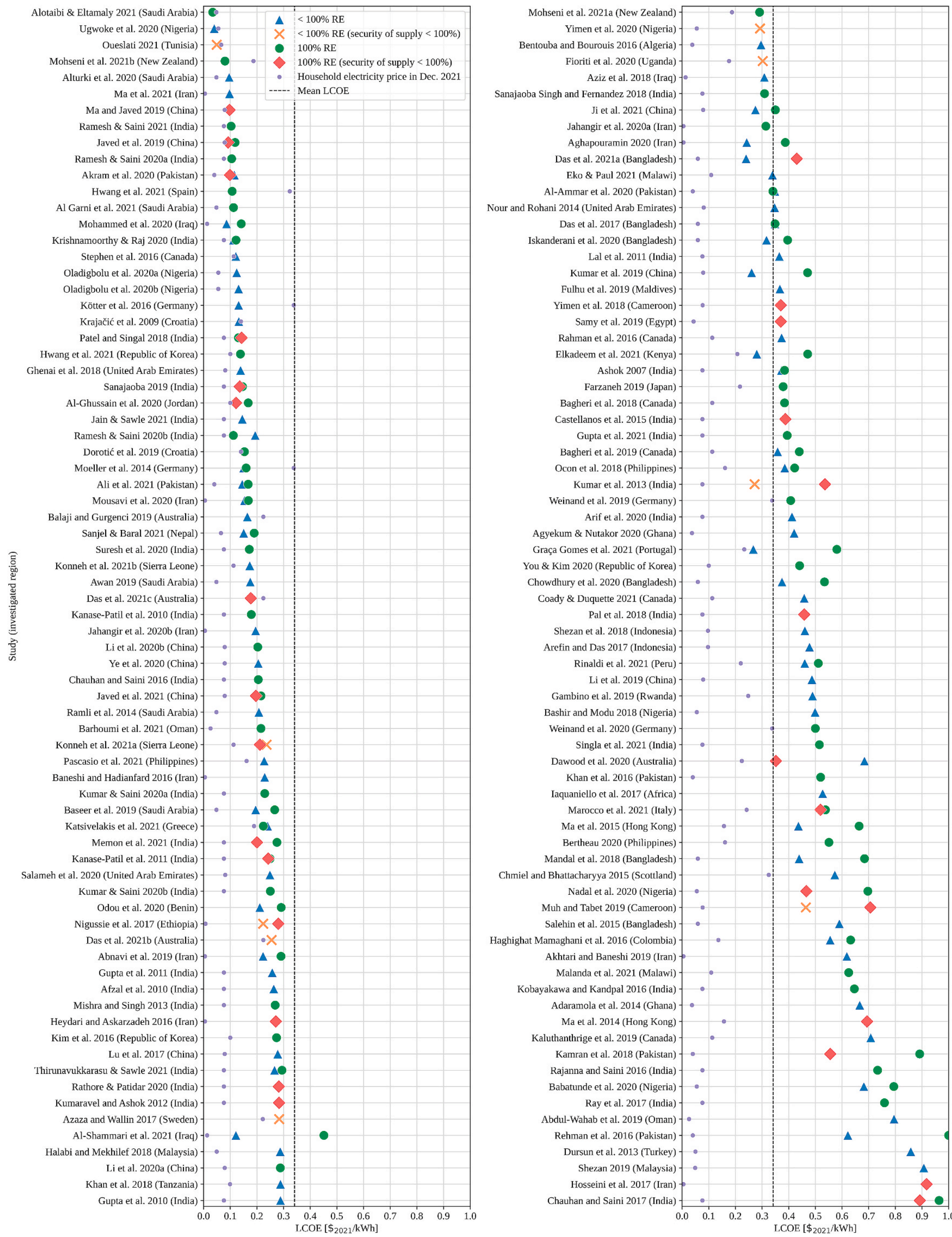

Fig. 1. Inflation-adjusted levelized cost of electricity (LCOE) for case studies on off-grid energy systems. The studies are sorted by mean LCOEs of all considered systems. Some hybrid systems consider fossil fuels and renewables (<100% RE) and some case studies incorporate only 100% renewable based systems (100% RE). The open-source Currency Conversion for Python (CuCoPy) [185] package was developed for this research and provides methods for exchanging currencies and adjusting monetary values for inflation. Its scope of application ranges from 1960 to 2021. Exchanging a value between currencies is done by dividing the target currency's exchange rate by the initial currency's exchange rate and multiplying the resulting quotient by the initial value. Likewise, adjusting for inflation is done by dividing the country's consumer price index at the starting date by its consumer price index from the target date. Most exchange rates and consumer price indices were provided by the World Bank Group and used under the CC BY 4.0 license [186]. The exchange rate used for converting Indian Rupees to U.S. Dollars in 2021 was not included in the data provided by the World Bank Group and was instead calculated by averaging the monthly exchange rate of Indian Rupee against U.S. Dollar provided on pages 104 and 105 in the "Economic Survey 2021–2022 Statistical Appendix" conducted by the Reserve Bank of India and published by Union Budget (India) [187]. In a few studies [42,100,149], LCOEs were given, but it was not clear for which country the case studies were conducted. Since it is not possible to adjust for inflation and no household electricity price can be stated for comparison, these studies are not included in the figure. The household electricity prices include all electricity bill items, such as the distribution and procurement costs, a variety of environmental and fuel costs, and taxes [188]. The right diagram is a continuation of the left diagram.

3.1. Reasons for overestimating LCOEs

While off-grid systems are generally associated with higher costs to meet load at all times of the year, a few studies show very high LCOEs, some above 1 $\$_{2021}$/kWh. Some LCOEs are particularly high due to high inflation in the countries studied, e.g., in the study from Askari & Ameri [46] for Iran from 2009. The following is an overview of some of the key drivers of why LCOEs have been overestimated in some studies.

Investment decisions as model input. Some studies using the energy system model HOMER present sub-optimal dimensioning of the autonomous energy system components. Chauhan et al. [65], for example, install an over-sized hydro power plant in each of their scenarios and the 100% renewable energy system results in 98% excess electricity per year and LCOEs of 2.99 $\$_{2021}$/kWh. Similarly, in Bashir & Modu [57], Rahman et al. [155] and Chang et al. [62], the energy systems also show 65%–92% excess electricity due to large oversizing of system components. The problem with these studies is that, due to the high combinatorial complexity of combined investment and dispatch optimization models [190], simulation models like HOMER are applied instead. This means that the dimensioning of the system components has to be done in advance and is not optimized within the model, which requires in-depth knowledge of the analyzed systems. Thereby, also backup and peak load capacities have to be considered, which are especially needed in case of extreme (weather) events. This makes it very complex to design an energy autonomous system with high supply security and cost efficiency. While it is possible to achieve comparable results with simulation approaches [191], an application of advanced models for investment and dispatch optimization should be carefully considered in the future to avoid overestimation of costs.

Ignoring technology cost degressions. Many articles did not adjust their cost assumptions to real developments. Especially in the last years, the mean of the assumed costs for photovoltaics (PV), onshore wind and battery storage in the studies is significantly above global cost trends, as shown in Fig. 2. Some notable examples include high PV costs of 2500 $\$_{2021}$/kW in the article by Malanda et al. [131] from 2021, 4200 $\$_{2021}$/kW in You & Kim [184] from 2020 or 5800 $\$_{2021}$/kW in Baseer et al. [56] from 2019. Particularly high wind or battery costs are found in Malanda et al. [131] from 2021 with 6000 $\$_{2021}$/kW for onshore wind or in Chang et al. [62] from 2021 with 1700 $\$_{2021}$/kWh for battery storage. The peaks in 2017 for wind turbine and battery costs are related to the fact that only two studies report costs and these are relatively high: the high maximum costs for batteries and wind turbines based on Hosseini et al. [90] are related to the strong inflation in Iran, and the high minimum cost for onshore wind are related to the cost assumption of about 5100 $\$_{2021}$/kW in Das et al. [71]. Since inflation-adjusted technology costs are compared with global cost developments in Fig. 2, these do not necessarily coincide. Still, this reveals that cost estimates tend to be pessimistic. Cost developments and influences could, for example, be covered by sensitivity analyses, but generally only few to no studies conduct these analyses with regard to techno-economic parameters. An exception is Nadal et al. [142], who comprehensively investigate ranges of capital and operational expenditures, replacement times etc. for PV, electrolyzers and batteries. They show for a microgrid in Nigeria that capital costs of PV and capacity loss of batteries are among the most influential parameters on LCOEs, which again illustrates the importance of sound cost choices.

Neglecting technology options. Not all articles consider comprehensive technology options. While solar PV is considered in all 100 studies and batteries in almost all articles (92%), this is not the case for other technologies (see Table 1). The importance of considering

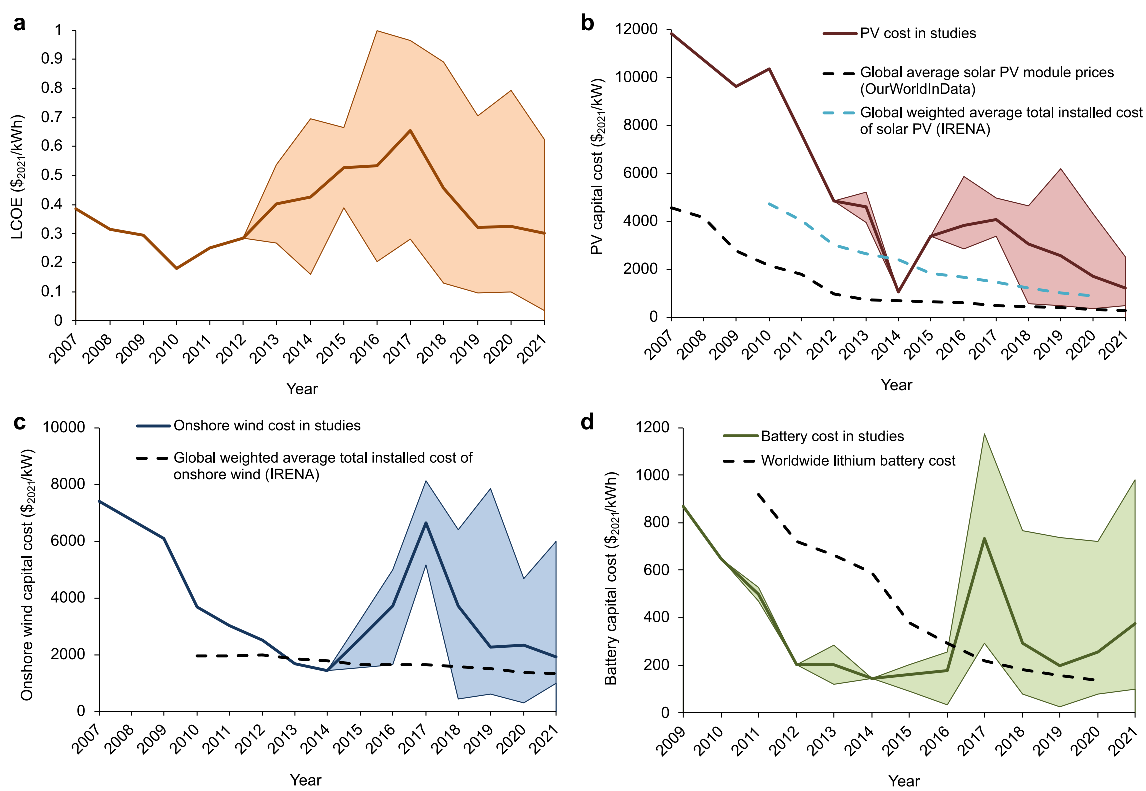

Fig. 2. Inflation-adjusted LCOEs (a) in 100 of the 161 studies, which consider 100% renewable energy systems without fossil fuels. PV capital cost (b), onshore wind capital cost (c) and battery capital cost (d) are only indicated in 89 of the 100 studies, i.e., 11 studies do not give information on costs. Due to their large impact on the cost curves, some very large outliers have been removed from a, b and c, see main text. The curves indicate the mean values among all studies and the area around them show the range between upper and lower extreme values. If no area surrounds the curve of mean values in a specific year, this means that either only one study was published in this year, or all used the same cost value. In panels a, b and c, the inflation-adjusted costs from the studies are also compared to real costs based on global averages. The global costs for PV are based on Refs. [192,193], for wind on Ref. [193] and for batteries on Ref. [194].

Table 1
Impact of neglecting specific technologies on LCOEs for 100% renewable off-grid energy systems in 25 case studies published in 2021.

	Wind power	Hydro power	Batteries	Electrolyzers, fuel cells and hydrogen storage
Share of studies not including this technology [%]	20	88	4	80
Mean LCOE increase if not included [%]	36	24	30	15

technologies comprehensively is shown by the fact that including onshore wind, hydro power, batteries or hydrogen storage, and fuel cells plus electrolyzers could reduce LCOEs on average between 15 and 36% (Table 1). This finding is in line with other research: a recent article has shown that neglecting onshore wind in municipal renewable energy systems leads up to about 0.08 $\$_{2021}$/kWh higher LCOEs for energy systems by 2050 [195]. Other studies show that incorporating base load capable technologies such as deep geothermal energy could also significantly reduce the cost of decentralized energy systems [179,180,196]. Particularly in off-grid energy systems, unconventional but potentially beneficial technologies and measures should also be incorporated in the future, e.g., higher shares of district heating [197,198] or the integration of large-scale hydrogen production [199]. In addition, sector-coupling options such as through electric vehicles (e.g., in Akthari & Baneshi [32] or Oldenbroek et al. [149]) or fuel cell vehicles (e.g., in Dorotić et al. [74] or Weinand et al. [179]) should be considered and have the potential to reduce LCOEs for off-grid systems.

3.2. Reasons for underestimating LCOEs

There are also some key drivers, which could have led to an underestimation of LCOEs and will be discussed in the following.

Neglecting grid integration. Costs for integrating variable renewables into energy systems are small at low penetration of renewables, but can rise sharply at high penetrations [200,201]. Parts of the system LCOEs for integrating renewables are profiling costs for dispatchable generation to meet the residual demand, balancing costs to balance forecast and actual non-dispatchable generation, and grid costs for grid reinforcements and extensions to integrate the renewable generators in the network [202,203]. While in the case studies on 100% renewable energy systems the balancing costs are included and the profiling costs are at least partially included, the grid costs are neglected with very few exceptions (see Moeller et al. [136] or Weinand et al. [179,180]). Many recent articles show that LCOEs are underestimated if not all system LCOE aspects are considered: for example, Chen et al. [204] show for China that the traditional LCOE approach underestimates wind generation costs by about 15% compared to a system cost approach. Furthermore, McKenna et al. [205] demonstrate in an onshore wind potential analysis for Great Britain that taking grid connection costs into account doubles the cost of a wind farm on average. Veronese et al. [206] derive similar conclusions for solar PV in the future Italian energy system revealing that the system LCOEs are on average 50% higher than in usual LCOE analyses. Thus, future studies on 100% renewable energy systems should attempt to incorporate all components of system LCOEs.

Applying hourly resolution. Das et al. [69] use the HOMER model to demonstrate for a PV/Wind energy system with lithium-ion batteries in a remote community in Australia, that the temporal resolution of the model has a negligible effect on the LCOEs. Their results show that the LCOEs decrease with lower temporal resolution from about 0.33 $\$_{2021}$/kWh at a minute resolution to 0.32 $\$_{2021}$/kWh at an hourly resolution. For that reason, Das et al. decide for an hourly resolution given a smaller computational load. To the best of the authors' knowledge, the remaining works subject to this review focus on hourly resolution exclusively. Potential reasons are the generally better availability of hourly resolved data bases and the moderate required model runtimes, but also software-related restrictions as more than 50% of the reviewed publications rely on the software HOMER or HOMER Pro. These models use a hybrid approach of optimization and simulation to design near-optimal, but reliable systems, which may distort the impact of different temporal resolutions.

Purely optimization-based capacity expansion models are well-known to underestimate real system costs at coarser temporal resolutions [207] due to unintentional peak-shaving of the duration curves resulting from averaging [208] and to thereby undersize system capacities, which leads to operationally infeasible system designs [209]. This effect is particularly strong for small and isolated renewable energy systems. These systems cannot use grid connections or the superposition of multiple demand profiles to level out demand peaks or supply troughs, leading to significantly higher overcapacities if the temporal resolution is increased [210]. Furthermore, the cost increase is degressive with higher temporal resolutions and therefore it is highly model-dependent whether the impact of an increased temporal resolution can be neglected or not. For that reason, different optimization-based publications focusing on different model scopes have arrived at different conclusions with respect to the impact of sub-hourly model resolutions: for the cost-optimal design of a hybrid municipal energy system with 250 households comprising PV and combined heat and power, Kools et al. [211] conclude that higher temporal resolutions lead to slightly higher load losses (3% for minutely resolution, 2% for hourly resolution) and smaller PV capacities. However, the authors demonstrate that the impact is small and should therefore be omitted for the sake of computational tractability. Harb et al. [212] arrive at a similar finding that the overall cost underestimation of less than 1% in hourly energy system optimizations of a small neighborhood compared to quarter hourly resolution is negligible. However, the general trend that higher resolutions lead to higher costs and smaller cost-optimal shares of non-dispatchable renewables (if dispatchable fossil sources are available) holds true as well.

Overall, the impact of sub-hourly resolved time steps on overall system costs likely remain small or moderate, but the systematic assessment of this aspect is too widely neglected to derive general conclusions. Especially with respect to the relative frequency of outage or lost load with usually very small percentage values, the impact may be considerable for 100% renewable off-grid systems.

Risk of social opposition. The vast majority of articles contain pure techno-economic analyses. Only a few studies combine this with multi-attribute [111] or multi-criteria [77,116] decision making to include preferences of stakeholders in the evaluation of energy systems. The disregard of social acceptance could lead to technically and economically optimal energy systems from a theoretical perspective, which cannot be implemented in reality, as decision-makers might reject certain technologies. Especially for onshore wind, the opposition of local inhabitants towards turbines due to landscape impacts [205,213,214] or disamenities [215,216] may be particularly strong and lead to higher system costs. Since many aspects regarding the techno-economic feasibility of off-grid renewable energy systems have already been extensively studied in the past, future studies should increase their efforts to incorporate more non-technical aspects in energy system analyses [217,218].

Transformation versus overnight expansion. Nearly all studies (96%) consider so-called overnight pathways, i.e., only the cost-optimal final state is planned for the energy system, but not the path leading there. Only four exceptions consider off-grid energy systems in a multi-year transformation [74,114,179,180]. Especially expansion rates of renewable energies as well as retrofit rates of buildings can have a major impact on costs and CO_2 emissions in decentralized energy systems [196] and could be limited by available material and craftsmen. Using a multi-year transformation planning together with model-endogenous technology learning could also avoid stranded investments due to installing technologies that are not needed in the future energy system [219].

3.3. Considerable impact of discount rate on LCOE

Another significant influence on the LCOE in energy system analyses can arise from the choice of the discount rate, which is country specific [220] and ranges from 0.3% for a case study in Japan to 18% for a case study in Iran, as illustrated in Fig. 3. Some studies also examine the effect of discount rate on LCOE for regional energy system case studies in Bangladesh [132], Canada [52], Cameroon [141], India [157], and China [125]. Thereby, the studies show that a 10% increase in the discount rate increases the LCOE by about 3–6%. Due to the higher specific investment and lower operating costs of renewables, the discount rate has a particularly high impact in renewable energy systems. For a hybrid off-grid energy system with a renewable penetration of only about 20%, Rahman et al. [155] demonstrate that an increase in the discount rate of 20% has a negligible impact on costs (+0.1%). In future studies on 100% renewable energy systems, the choice of the discount rate should be made very carefully to avoid underestimation or overestimation of system costs.

4. Discussion

This review reveals the decrease in costs for decentralized off-grid renewable energy systems due to technological progress and cost degression. Recent global energy, health and geopolitical crises and the associated rise in retail energy prices could make off-grid energy systems worthwhile even in certain regions of industrialized countries. As has been shown for a few countries, the household electricity price is already higher than the LCOEs calculated in some case studies for off-grid energy systems.

Additionally, seven key reasons that lead to a systematic overestimation or underestimation of costs in the model calculations have been identified. To avoid an overestimation of LCOEs, future studies should carefully size energy technologies in simulation models (1), integrate all recent cost developments (2) and include all potentially beneficial technology options (3). To prevent underestimation of costs, integration costs should be accounted for (4), higher temporal resolutions should be applied in combination with time series aggregation approaches (5), social opposition to certain technologies in the regions studied should be addressed (6), and pathways for the transformation of energy systems should be planned instead of only planning the final state of systems (7).

Further suggestions have recently been developed by a group of experts. As an energy system reaches 100% renewable energy, the necessary balance between supply and demand usually leads to a highly nonlinear increase in costs, mainly due to seasonal mismatches [17]. Since reaching the last 10% to achieve a completely renewable energy supply is especially challenging, the group of experts introduced six strategies for this [16]: building more variable renewable energy together with transmission and diurnal storages (1), installing other base-load capable renewable energy technologies like geothermal energy, hydropower or biopower (2), deploying nuclear plants as well as fossil-based ones with carbon capture (3), using seasonal storage by hydrogen, storage and re-electrification (4), employing carbon dioxide removal like bioenergy with carbon capture and storage (BECCS) or direct air carbon capture and storage (DACCS) (5) or intensifying demand-side measures like demand response or demand flexibility (6). While some of these strategies are more suited for large centralized energy systems (e.g., installing conventional nuclear power plants) or fully decarbonized energy systems (BECCS and DACCS), they are consistent with the recommendation in Section 3 to exploit all available technological options to achieve 100% renewable energy systems in the future in a cost-effective way.

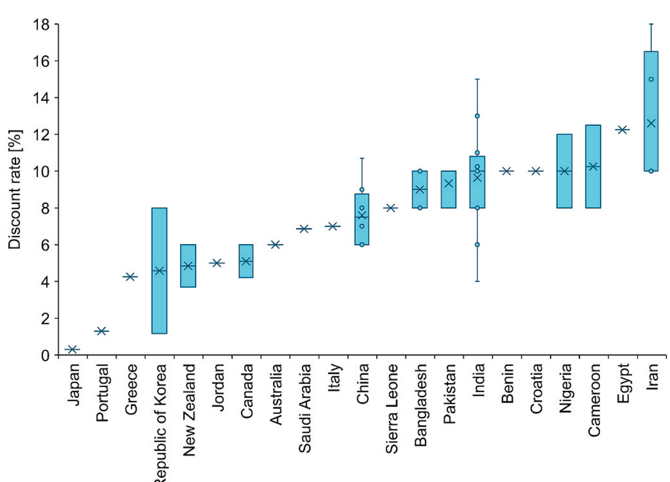

Fig. 3. Box plots of discount rates in 59 articles on 100% renewable off-grid energy systems, classified by country in which the case study was investigated. 41 articles on 100% renewable off-grid energy systems do not state the value of the discount rate.

While this review attempts to present the LCOEs of off-grid regions in various countries as comparable as possible by adjusting for inflation, the heterogeneity of regions in, for example, size, energy demands, renewable potentials, and cost structures [221] means that the LCOEs between studies can never be completely comparable. In addition, the discussion on system LCOEs in Section 3 indicated that LCOEs may not be the best and most comprehensive metric to compare energy systems. Recently, a new metric called the Cost of Valued Energy has been introduced to better evaluate energy systems with high shares of renewable energy. The Cost of Valued Energy relies on system costs in relation to spot market revenue on an annual basis and thus takes into account not only the economic impact of supply vs. demand but also of cost vs. revenue [222]. Although spot markets could be irrelevant in decentralized off-grid energy systems, this highlights once again the need for novel metrics to compare energy systems. While the COVE places a higher value on energy supply during high wholesale energy prices, in off-grid systems the supply could be weighted stronger, for example, during periods of dark doldrums or demand peaks.

Besides cost considerations, off-grid energy systems should be assessed by means of environmental metrics and social aspects to achieve a more thorough energy systems analysis. Life cycle assessment can be used to quantify the environmental impacts of a product, service, or energy system over the entire life cycle (including the manufacturing, operation, and end-of-life phase), considering environmental impacts beyond greenhouse gas emissions [223]. Thus, life cycle assessments can identify potential trade-offs between costs, greenhouse gas emissions, and other environmental burdens [199,223]. Off-grid energy systems can be decarbonized by abandoning the import and use of fossil fuels, integrating low-carbon energy sources – such as solar PV and wind – and using energy storage [199]. However, the manufacturing of off-grid energy systems can result in environmental burden shifting, for example with regard to material utilization and/or land occupation [199,224]. In line with Section 3.1, these additional environmental burdens mainly arise due to the oversizing of off-grid systems, which might be reduced with optimization and/or appropriate disposal of system components. Thus, there can be substantial environmental consequences when costs are the only metric considered within the analysis of off-grid energy systems. Therefore, additional metrics beyond costs and (operational) greenhouse gas emissions during the design phase of off-grid energy systems must be considered.

However, LCOEs are the only suitable metric to compare the economics of decentralized off-grid renewable energy systems at the moment, due to their coverage in most studies. The comparison with the LCOE overview in this review can, for example, prevent design errors in future studies, if authors find that their calculated LCOEs are too high or low. Therefore, this overview can be used to verify findings on off-grid systems, to assess where these systems might be deployed and how costs evolve.

This review provides concrete implications for policy makers, investors and researchers in most if not all of the analyzed countries (as well as learnings in those not included). As many of these countries attempt to transition towards a mainly or fully renewable energy system, they all face the same challenge of integrating variable renewable energy technologies. The cost of the required measures, including network expansion/densification, storage, backup capacity, and flexibility of existing plants, can be reduced in some cases with off-grid energy systems. Especially in countries where grid parity has made the self-consumption of self-generated energy (power) more economical than imported energy (power) from the grid, but also as recent geopolitical events have motivated some pro/consumers to pay a premium for a more secure, local energy supply, such renewable-based micro- or minigrids can increasingly represent an economically and environmentally attractive opportunity compared to conventional centralized energy supply structures. Furthermore, as approaches to energy communities become more established, such local networks of self-supply can start to emerge at scales from individual buildings up to whole cities, whereby the precise size and configuration, and therefore the economic business case, depends on local supply and demand characteristics. The challenge for policymakers and regulators is to create the right incentives and signals that encourage these off-grid initiatives in locations and at scales that are Pareto optimal, in other words where the local consumers benefit but at no detriment to the overarching energy system.

Credit statement

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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.

Data availability

Data will be made available on request.

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