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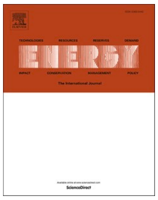

SLCOE – system-based LCOE for comparing energy technologies in different systems ☆

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ABSTRACT

Levelized cost of electricity and Levelized cost of energy (LCOE) have been used to identify how different energy technologies compare in terms of cost, where LCOE identifies the cost of the production of one unit of electricity or energy. This includes investment costs, operation and maintenance costs, fuel costs, non-subsidized emission costs, etc. However, LCOE represents a simplistic comparison that does not capture the innate differences between production technologies. Renewable energy sources depend on weather patterns; steam turbines based on nuclear, coal or biomass have certain flexibility constraints, and gas turbines offer less constrained flexibility. In this study, we introduce a system-based LCOE - referred to as SLCOE. While the LCOE is only a function of the respective technology, the SLCOE is a function of both the technology and the energy system context in which it operates. We show how the SLCOE of wind power and solar photovoltaics can be much lower in the integrated energy systems of a future climate neutral society than in the existing electricity system. We illustrate how the SLCOE of combinations of wind power and solar photovoltaics can be much lower than the SLCOE of the individual technologies. Moreover, we compare renewable energy sources with nuclear power and find that with the current as well as expected future costs of these technologies, the SLCOE of nuclear power is substantially higher than for renewable energy.

1. Introduction

Working towards the most efficient decarbonization of the energy systems globally, identifying and comparing various technology options, is a key component in decision making. The main comparison form, on a per unit basis, is the calculation of the levelized cost of energy (LCOE). The purpose of LCOE is to calculate the long-term marginal cost of producing one unit of energy, for instance expressed in USD/MWh. To calculate the LCOE, all costs in the lifetime of a technology are included. In addition, all costs are discounted over the lifetime of each technology.

While this provides valuable insight into the costs of a unit of energy for a specific technology, it does not provide the full picture of the technology, especially in the case of a carbon neutral energy technology. For instance, renewable energy technologies, such as wind power and solar photovoltaics (PV), are variable generating units that are dependent on weather patterns. Even though solar PV often peaks at the same time as electricity demands and integrated wind-solar farms create relatively stable energy as pointed out in Ref. [1], they cannot produce all the time and are limited to downward regulation in terms of matching demands. Nuclear power requires heavy CAPEX investment,

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has limited generation flexibility, and worldwide the average capacity factor in 2024 was only approx. 79 % [2]. Thus, nuclear requires substantial back-up and peak-load power. Indeed, nuclear power requires some of the same flexibility as systems based on variable renewable energy sources [3]. Hence, not all energy outputs are equal when they must match an energy demand. Several papers and reports suggest alternatives to LCOE to allow for a better comparison between technologies.

The International Energy Agency (IEA) proposes and compares technologies based on the concept of Value Adjusted Levelized Cost of Energy (VALCOE) [4]. VALCOE adjusts the traditional LCOE by analysing how the technology provides value for the system. This is done by including three elements for adjustments: energy, capacity and flexibility. The adjustment is made by comparing the estimated value elements for each technology with the system average. Energy is adjusted based on hourly wholesale electricity prices; capacity is adjusted based on capacity credit, a capacity value and capacity factor, and flexibility is adjusted based on a flexibility value multiplier, a base flexibility value which is a function of the annual share of renewables in generation. Hence, the flexibility value inherently increases up to a maximum equal to the full fixed capital recovery cost of a peaking plant. The VALCOE methodology incorporates some system perspectives in the sense of adjusting based on an average system. However, it cannot capture the influence of the expansion rate of the technology in question. This means that the VALCOE methodology fails to include the aspect of how different system layouts can impact the value adjustment.

Ueckerdt et al. [5] suggest introducing a system LCOE to identify the costs of variable renewable energy sources (VRES), on the premise that comparing LCOE between VRES and dispatchable technologies is flawed. The objective of the study is to illustrate how a system LCOE is the sum of the traditional LCOE and the marginal costs of the variability that occurs at a system level. Ueckerdt et al. identify the difference in costs between a system with and without the given technology as the basis of such a system LCOE, e.g., a system with and without VRES. Hence, the difference in costs if both systems are balanced would be the integration costs. While this is a reasonable perspective, Ueckerdt et al. continue to discuss the additional cost, which consists of grid costs, balancing costs and what they refer to as profile costs. They break the profile costs into three main effects: 1) VRES reduce the full-load hours of existing plants, 2) VRES do not impact the overall demand for electricity capacity, as VRES cannot produce all the time, and 3) with an increased VRES share, curtailment will happen more frequently, which also leads to an economic loss as this is “wasted” energy.

Three aspects are important to discuss. First, the suggested approach does not take into account the transition of the entire energy system, and as we shall see later, this can have a major impact on the results. Secondly, it can be discussed whether it is meaningful to associate the economic losses in other technologies directly with a single VRES investment. Lastly, it is a problem to assume that curtailment provides an economic loss beyond reducing capacity factors. For these reasons, the results of Uerckerdt et al. are most likely exaggerated. Emblemsvåg [6] also discusses LCOE from a renewable energy perspective but does not conduct a full energy system analysis and only reviews the system costs as associated with the renewable energy producer [6].

Graham [7] reviews a number of alternatives to adjust LCOE, concluding that a system analysis needs to be implemented to review the system costs of renewable energy. This is in line with the aim of this study. However, the research presented here has the objective of not only including options in the electricity system and electricity system modelling, but to include the entire energy system, utilizing sector coupling and smart energy systems [8–11] to calculate system LCOEs.

Heptonstall and Gross [12] conduct a literature review to quantify how integration costs impact the costs of renewable energy. Within the review, they discuss the concept of operating reserves, capacity adequacy and profile costs. Similar to Ueckerdt et al., from the literature study, they plot and discuss how the different costs vary depending on the share of renewables. Hepstonstall and Gross highlight a number of risks, when discussing these different cost components as they might overlap and lead to double counting which would result in an overestimation of the value adjusted costs of renewable energy. Hence, they conclude that one cannot simply add individual components on top of each other and then argue to have been looking at the energy system as a whole.

System-level LCOE is reported in the research of Breyer and Bogdanov et al. for studies covering the power sector [13], the energy system [14], and the energy-industry system also including chemical industry [15]. For a differentiated discussion, they report the levelized cost of electricity, but also the levelized cost of final energy, and for the case of industrial feedstock inclusion, they also include the levelized cost of final energy and non-energy use. They define the specific levelized cost as the total annualized system cost divided by the total final energy demand with the cost metric reported in EUR/MWh. This approach has the advantage that the total system costs are included in full, such as storage, grids, but also curtailment, whereas for the case of a full energy system, or energy-industry system, the various flexibility options of sector-coupled systems are also taken into account. This specific cost metric allows an effective comparison of scenarios that can reveal the lack of ambitious renewable energy development, but also show that giving priority to higher cost renewable energy options will regularly lead to higher system-level LCOE [16]. The disadvantage of this approach is that the levelized cost is aggregated at the system level, which means that individual technology contributions are no longer traceable. However, once a system cost has been established, sensitivity tests can readily be run to estimate the impact on cost of one technology compared to another, as done in Jacobson [17].

Hansen [18] follows a similar approach by using the entire energy system costs but associates the increased/decreased costs with a specific technology. However, the approach misses potential changes to system designs across sectors when measuring the individual technology. Furthermore, Hansen does not define a specific system cost to be associated with the technology.

In sum, it is clear that to assess the system costs of any technology, the only meaningful way is to conduct an analysis of the entire energy system. Without a system approach and without considering the entire energy system, the value adjustment risks double counting or does not include the full array of flexibility measures available to integrate renewable energy sources. A recent literature review of more than 1000 studies on 100% renewable energy system analyses revealed at least 22 different types of flexibility [19], which can be grouped into five major categories: power-to-X, storage, demand response, grids, and curtailment. It was also found that the sector benefitting most types of flexibility is the power sector, which also documents its central role in future energy systems that may be best characterized as Power-to-X Economy [20]. The suggestion of this study is therefore to introduce a system-based SLCOE, which highlights the need for system analysis. The use of SLCOE also shows that with a large shift in the energy system, the flexibility measures are dealt with in a more cost-efficient manner than enabled by LCOE, VALCOE and other methodologies, as these are simply too narrow in their understanding of flexibility requirements. Other potential costs such as health and social costs are disregarded in this study but can potentially be included as suggested by Robalo-Cabrera et al. [21].

2. Methodology

This study calculates LCOE and SLCOE for nuclear power, solar PV, offshore and onshore wind power in Europe and compares these costs of the present energy system with the future energy system of a climate neutral society. Moreover, it identifies least-cost combinations of these technologies.

In general, the LCOE is a function of the technology itself including surroundings such as weather and landscape, but not a function of the other parts of the energy system. While the LCOE is a function of the technology in question, the SLCOE is a function of both the technology and the energy system in which the technology operates. For the same LCOE of a certain technology, the SLCOE may differ between energy systems. Therefore, the value of a SLCOE does not make much sense unless one specifies and defines the energy system in question.

LCOE = f (technology)

SLCOE = f (technology, energy system)

From a theoretical and mathematical point of view, LCOE and how to calculate it is well defined. In this study, we define SLCOE as an LCOE plus the system cost of utilizing the technology in a given system. In the assessments, we have focused on the system costs of overcapacity of the technology itself, electrolysers and hydrogen storage, back-up power, influence on spinning reserve and transmission.

For practical reasons, this study uses Denmark as a case of a present and future energy system, since previous studies have implemented a detailed model of the energy system of a climate neutral society in 2045. Thus, some of the conclusions are specific for the case of Denmark. However, the theoretical and methodological conclusions are general.

The case includes all parts of the energy system (electricity, heating, cooling, industry, domestic transport and shares of international aviation and shipping). It is restricted to the use of sustainable biomass and is coordinated with other greenhouse gas emitting sectors such as agriculture, LULUCF (Land Use, Land-Use Change, and Forestry) and industrial processes to achieve a fully climate neutral society. Moreover, the base model of the Danish energy system is fully validated against Danish Energy Statistics. The case is described in detail in four published studies [22–25].

With the aim of a climate neutral society, it becomes essential to take a holistic smart energy systems approach [26] to identify least-cost storage [27] and electricity balancing solutions [28]. Thus, all scenarios and alternatives shown in the following have been analysed using EnergyPLAN and calculated for all technologies hour-by-hour for a full year including all types of storage capacities. EnergyPLAN is designed to take a smart energy systems approach [29–32] to the analysis of the need for energy security as well as energy storage and electricity balancing in a future climate neutral society. We have shown and quantified that the best solutions to the transition can only be found by taking a cross-sectoral holistic approach – also known as a smart energy systems approach [33].

For the calculation of the SLCOE, all technologies are compared under the same biomass restriction, and system costs include investments in flexibility, back-up power and balancing as well as transmission.

For nuclear power, an availability factor of 80% is assumed, and this value is applied as the capacity factor in the LCOE calculation. This corresponds to a required reserve capacity equal to 25% of the hourly peak electricity demand. However, such requirements for reserve capacity may also be provided by the use of electricity storage in least-cost alternatives of combinations of nuclear power and electricity storage. The same 25% reserve capacity factor is used for the other alternatives either as overcapacity of the CCGT power plant or as electricity storage.

The case of the Danish energy system has been used to identify an “electricity-only” system representing today's electricity supply in which there is hardly any electrification of the other sub-sectors yet, and “a climate neutral” system in which a full electrification of the heating, cooling, industry and transport sectors is implemented. In the electricity-only system, the electricity demand is 43.77 TWh with an hourly peak demand of 7915 MW and thus a need for installed capacity including 25% reserve capacity equal to 9894 MW.

In the energy system of a climate neutral society, the electricity demand will increase due to electrification by a factor of 2-3. In this study, the factor is 2.5 and is composed of an increase in new flexible demands of PtH, EV (V2G) and PtX (electrolysis). In such a system, more (and better) options of system integration arise compared to the electricity-only-system.

The following system cost options are used in the electricity-only systems.

- Overcapacity of the technology itself (nuclear power or solar PV, etc.).
- Electricity storage defined with the cost assumptions in Table 4.
- Peak load OCGT (in the case of CCGT and the least-cost mix under sustainable biomass restrictions).

The following system-cost options are used in the climate neutral energy system.

- Overcapacity of the technology itself (nuclear power or solar PV, etc.).
- Electricity, thermal and gas, oil, and hydrogen storage defined with the cost assumptions in Table 4. However, as we shall see, in such a system electricity storage cannot compete with the other options.
- Flexible use of heat pumps and electric boilers (PtH) in combination with thermal storage.
- Flexible use of EV (and V2G).
- Flexible use of PtX in combination with overcapacity of electrolysis and hydrogen storage.
- Peak load OCGT.

The key point is that a sector-integrated smart energy system in a future climate neutral society provides significantly more, and superior, opportunities for system integration than an electricity-only power system.

2.1. IEA WEO cost assumptions

We establish a common benchmark for the analysis by adopting the same cost assumptions for future nuclear and renewable energy investments in Europe in 2050 as those used by the IEA in its World Energy Outlook (WEO) reports. The data and calculation method have been adjusted with the aim to reproduce the IEA's LCOE results as a starting point. For the remaining technologies in the wider energy system, we apply cost assumptions from the consensus-based technology catalogue published by the Danish Energy Agency (DEA). We have identified costs from both the WEO 2023 [34] and WEO 2024 [35] reports. Moreover, we use DEA cost estimates for renewable energy technologies from both before and after the recent period of inflation and supply-chain bottlenecks, represented by the DEA cost expectations for 2020 and 2025. The costs are expressed in the price level of 2020-2022 (see explanation in Table 4).

For the main calculations, we have used the cost assumptions of the WEO 2023 report. The other three cost assumptions have been used for the sensitivity analysis.

The IEA WEO numbers are shown in Tables 1a and 1b.

As shown in Tables 1a and 1b, the IEA assumes a capital cost for

Table 1a

Technology cost assumptions and resulting LCOEs as they have been listed in the IEA report World Energy Outlook 2023 for Europe year 2050 (Table B.4a, page 301) [34].

Year 2050	Capital costs (USD/kW)	Capacity factor (%)	O&M (Fuel and CO2) (USD/MWh)	LCOE (USD/MWh)
Nuclear	4500	80	35	110
Gas CCGT	1000	10	130	n.a.
Solar PV	450	14	10	35
Wind onshore	1610	30	15	55
Wind offshore	1740	59	10	35

Table 1b

Technology cost assumptions and resulting LCOEs as they have been listed in the IEA report World Energy Outlook 2024 for Europe year 2050 (Table B.4a, page 333) [35].

Year 2050	Capital costs (USD/kW)	Capacity factor (%)	O&M (Fuel and CO2) (USD/MWh)	LCOE (USD/MWh)
Nuclear	4500	75	35	125
Gas CCGT	1000	10	120	n.a.
Solar PV	340	14	10	25
Wind onshore	780	30	10	25
Wind offshore	1660	56	10	35

nuclear power of 4500 USD/kW, O&M of 35 USD/MWh and capacity factors of either 75% or 80% leading to LCOEs of 110 USD/MWh in the WEO2023 report and 125 USD/MWh the WOE 2024 report. The capital costs are indicated as "overnight cost" and to match the resulting LCOEs, these numbers are treated with discount rates and construction periods. Especially for nuclear power, the expected WEO capital costs are substantially higher than the overnight costs due to the long construction times.

Moreover, in the IEA report [34], Bouckaert et al. [36] differentiate between low project risk technologies such as onshore wind power and solar PV, and high project risk technologies such as nuclear power. To reflect this, Bouckaert et al. [36] use a discount rate of 8% for nuclear power, while renewable energy technologies are assessed by a discount rate of 3-7%.

Based on these assumptions, we have been able to replicate the IEA WEO calculations and achieve the same results in terms of LCOE as shown in Tables 2a and 2b.

The capital costs have been rounded. We have not found it worthwhile to differentiate between variable and fixed O&M costs for renewables and nuclear power, since for these technologies the variable O&M costs are very small. However, for the CCGT, we have differentiated between fuel, variable and fixed O&M costs. The O&M costs for CCGT in Tables 2a and 2b are the sum of the fuel costs of 52 USD/MWh and fixed O&M costs of 6 USD/MWh and variable O&M costs of 3 USD/MWh. The very high LCOE of the CCGT is mainly due to the low capacity factor. At a capacity factor of 80% instead of 10%, the LCOE is around 70 USD/MWh.

When applying these numbers to the scenario analysis using the EnergyPLAN model, it is only possible to enter one discount rate, and we have used 5% in all the analyses. Rather than applying a separate 8% discount rate for nuclear power, we model its effect by increasing the capital cost. This approach produces the same outcomes as using differentiated discount rates.

As already mentioned, this study has a point of departure in the WEO2023 cost assumptions and resulting LCOEs as illustrated in Fig. 1.

2.2. Discussion of WEO/IEA cost assumptions and sensitivity: Nuclear power

As described above, WEO/IEA assumes an overnight cost for nuclear power of 4500 EUR/MW in 2050. The capital costs for nuclear power represent the so-called "nth-of-a-kind" costs for new reactor designs, with substantial cost reductions from the first-of-a-kind projects. With an interest rate of 8% and a construction time of 9-12 years, this corresponds to a CAPEX of 6500 EUR/MW (WEO2023) and 7300 EUR/MW (WEO2024), respectively. It should be noted that the expectation of a declining CAPEX for nuclear power does not align with the documented experience of nuclear power for a period of more than five decades [37,38]. Thus, the assumption of declining costs must be considered as optimistic. A literature review on nuclear power learning rates found a range of −25% to 0%, which indicates that nuclear has the least favourable value of all power generation technologies [39]. The realized CAPEX in recent nuclear power projects in Europe exceeded the values as listed in this paragraph [40] which indicates a high risk for additional cost overruns, typically in the order of about 100% of the initial cost estimates [41]. Discussion on small modular reactors (SMR) is ongoing in several countries [42,43]. SMRs are expected to reach lower total investments per plant due to the smaller size compared to large-scale nuclear power; however, this leads to higher CAPEX due to negative economies of scale which cannot be compensated by the expected learning rate of the modular approach. The compensation can only be achieved if very large SMR capacities are built based on standardised SMR designs, and this is hardly achievable given the considerably higher CAPEX of SMRs versus large-scale nuclear power, which is expected in the range of 10,000–15,000 EUR/MW in the 2030s [44]. Based on fundamental economic considerations, SMRs are not competitive compared to large-scale nuclear power plants.

In Fig. 2, we have compared these expectations to recent costs in Europe. For realized and almost realized plants, we have shown both expected costs before construction as well as final costs after construction. As illustrated, for nuclear power, there is a significant difference. This uncertainty is included in the WEO/IEA calculation of LCOE by assuming a high interest rate of 8%, while 5% are used for solar PV and wind power. This difference equals a CAPEX for nuclear power as high as 10,000 EUR/MW. This means that a CAPEX of 6500 EUR/MW in combination with an interest rate of 8% equals the same annual CAPEX as 10,000 and 5%. In the case of WEO2024, the 7300 and 8% equal the same annual CAPEX as 11,200 and 5%.

As shown in Fig. 2, these expectations correspond to the recent trend in increasing costs. In this study, the WEO2023 cost of 10,000 EUR/MW is used in the main scenario with two alternative costs for the sensitivity analysis: One using the WEO2024 costs of 11,200 EUR/MW and another using only 6500 EUR/MW. The second represents an alternative in which the same interest rate of 5% is assumed for all alternatives or an alternative in which overnight costs are as low as 3000 EUR/MW instead of 4500 EUR/MW, while still using 8%.

2.3. Discussion of WEO/IEA cost assumptions: Renewable energy

The cost assumptions of wind power and solar PV are quite different between WEO2023 and WEO2024.

In WEO 2023, the combination of a high-capacity factor and a low CAPEX for offshore wind power makes this technology superior to onshore wind power in every aspect. Thus, with these assumptions, it

Table 2a

Replication of the IEA report World Energy Outlook 2023 of Table 1a.

Year 2050	Overnight costs (USD/kW)	Discount rate (%)	Construction time (Years)	Capital cost (USD/MWh)	Lifetime (years)	Capacity factor (%)	O&M (not CO2) (USD/MWh)	LCOE (USD/MWh)
Nuclear	4500	8	9	6500	60	80	35	110
Gas CCGT	1000	5	2	1000	30	10	61	135
Solar PV	450	5	4	480	30	14	10	35
Wind onshore	1610	5	1	1610	30	30	15	55
Wind offshore	1740	5	5	1950	30	59	10	35

Table 2b
Replication of the IEA report World Energy Outlook 2024 of Table 1b.

Year 2050	Overnight costs (USD/kW)	Discount rate (%)	Construction time (Years)	Capital cost (USD/MWh)	Lifetime (years)	Capacity factor (%)	O&M (not CO2) (USD/MWh)	LCOE (USD/MWh)
Nuclear	4500	8	11-12	7300	60	75	35	125
Gas CCGT	1000	3	2	1000	30	10	61	119
Solar PV	340	3	2	350	30	14	10	25
Wind onshore	780	3	1	780	30	30	10	25
Wind offshore	1660	5	5	1890	30	56	10	35

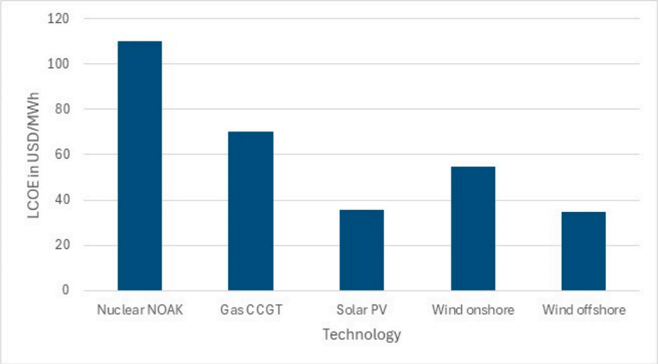


Fig. 1. Illustration of resulting LCOEs as they have been listed in the IEA report World Energy Outlook 2023 for Europe year 2050 (Table B.4a, page 301) [34].

will not pay to build onshore wind power at all.

In the WEO 2024, the CAPEX of onshore wind power is substantially lower than offshore, while the capacity factor of offshore is higher than for onshore. This is also the case for actual historical costs in Denmark as well as for cost assumptions used by the Danish Energy Agency (DEA 2020). With such an assumption, the least-cost solution will be a combination of onshore and offshore wind power.

The above cost assumptions do not capture the recent increase in CAPEX caused by inflation in 2023 and onwards. A study on offshore wind power in Denmark reveals an expected increase of around 50% in investment costs, divided into an increase of 40-50% in wind turbine costs and 50-60% in high voltage cables and equipment costs.

To capture such changes, we have defined a set of inflation corrected costs of renewable energy simply by adding 50% to the CAPEX and 20% to the OPEX of the DEA 2020 costs. These assumptions are here called DEA2025. By applying these factors, the sensitivity analysis sufficiently applies economic costs more expensive than documented in the latest Danish Energy Agency's technology catalogue, which includes updated, increased costs, to offshore wind power [45].

As already mentioned in the section on nuclear power costs, we use the WEO2023 as the base calculation and use the other cost assumptions as sensitivity analysis.

As we will see later, such changes in assumptions increase the cost of renewable energy but do not change the overall picture of the results as such.

2.4. *Transmission system capacity and costs*

Due to lower capacity factors, the alternatives with wind power and solar PV have a higher peak production than the alternative with nuclear power. Some of these peaks are curtailed while others are utilized via changes in the flexible demands. Consequently, these alternatives will

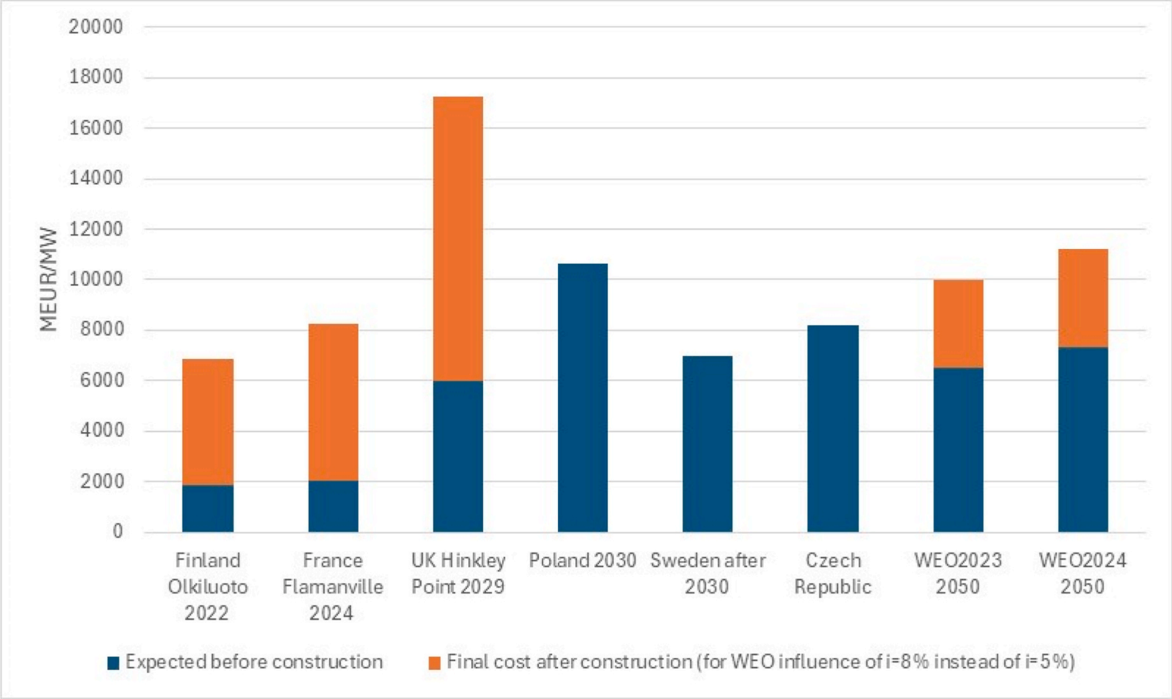


Fig. 2. Comparison of IEA 2050 cost assumption to recent CAPEX costs in Europe. Using 8% for nuclear and 5% for other technologies equals a CAPEX for nuclear of 10,000 EUR/MW instead of 6500 EUR/MW (WEO2023) and 11,200 EUR/MW instead of 7300 EUR/MW (WEO2024).

also imply higher electricity grid costs. How much higher depends on the configuration of both supply and demand.

In the alternatives of the wind power and PV-based climate neutral society, peak productions of the supply will primarily be matched through demand increases of electrolysis in PtX facilities, which will typically be large units connected to the transmission grid rather than to the distribution grid. In general, the differences in the distribution system between wind- and PV-based systems and nuclear-based systems are minimal, as the distribution grid demand is the same in all modelled scenarios. Minor differences may be seen in the operation of, e.g., heat pumps in district heating systems. However, these units are located at district heating plants that are already connected to the grid with higher-capacity CHP units.

For actual grid expansion planning, detailed analyses of the spatial distribution of future production and demand are required. Furthermore, cost assessments are influenced by whether potential new lines are overhead lines or underground cables and for instance whether an existing overhead line has room for more circuits on the same set of pylons. An estimate of the transmission system cost difference between the alternatives has therefore been made according to two provisional approaches for the case of Denmark; one according to the length of the existing system and expansion costs and one according to existing expansion plans to accommodate an ongoing quadrupling of wind power and PV.

The existing Danish transmission grid consists of 2900 km of overhead lines at 132, 150 and 400 kV AC as well as HVDC and a total of 3200 km of underground and undersea cables including both HVAC and HVDC [46]. The 3200 km includes the Danish share of HVDC and HVAC interconnectors to Germany, Sweden, Norway, the Netherlands and the United Kingdom. Also, the given distances are for circuits, not for lines, which means that a double-circuit 400 kV system counts twice and, e.g., multiple parallel HVDC interconnectors are counted multiple times. With these notes, this gives a total of approximately 6100 km. The specific composition is not in the public domain, but an estimate splits this into 1500 km at 400 kV, 1800 km international connections and the connection between the two pricing areas of Denmark, 400 km of connections to offshore wind farms leaving approx. 2400 km at 132 and 150 kV. With a few exceptions, the 400 kV part is overhead lines, whereas the 150 and 132 kV lines to a higher extent are underground cables.

According to the Danish TSO Energinet [47], the cost of expanding 400 kV lines is [37] approx. 500 EUR/MW/km for overhead lines and approx. 1500 EUR/MW/km for underground cables. Thus, the cost of expanding the 132/150/400 kV transmission grid would be in the order of magnitude of 2 MEUR/MW using a mix of the specific 400 kV overhead line and underground cables. 132/150 kV lines are cheaper per kilometre, but they also carry less power. In addition, new lines at this voltage level are often built as underground cables, which further increases costs. Using the 400 kV cost is thus not an unreasonable estimate [48]. However, this cost may be used under the assumption that the entire grid would have to expand as a direct consequence of any RE capacity expansion, thus without including spatial or temporal characteristics or any potential unexploited capacity in the present transmission system. Thus, it is clearly an overestimation.

A fully expanded grid would allow all supply and all demand to be connected through a single access point at any location. In practice, this level of expansion is unnecessary. For example, if supply and demand share the same access point, no grid reinforcement is required, assuming their timing aligns perfectly. Typical cases of offshore wind power and nuclear power will have 5-10 access points of supply and maybe the same will apply to significant point-demands like PtX facilities. For onshore wind power and solar PV, this number will be much higher and the need for grid expansion will be correspondingly lower. This consideration leads to an estimate of a transmission system expansion cost of, e.g., 0.5 MEUR/MW for nuclear power and offshore wind power and a lower number for onshore wind power and solar PV.

Another way of making an estimate is to use the Danish TSO costs of 41 billion DKK or 5.5 billion EUR [49] of expanding the grid towards 2026 and a similar amount towards 2030 to be able to deal with the policy of the Danish Government to quadruple the Danish production of onshore wind power, solar PV and offshore wind power. According to the Danish Energy Agency [50], solar PV, onshore wind power, and offshore wind power capacities will expand from 3115 MW, 4864 MW, and 2306 MW, respectively, in 2023 to 20,619 MW, 7314 MW, and 5351 MW, respectively, in 2030. This will result in an expansion of 23 GW of renewable capacity between 2023 and 2030. Using these inputs, the implied transmission grid expansion cost is approximately 0.4–0.5 MEUR per MW of additional renewable energy capacity. This estimate includes the cost of transformers, which were not part of the length-based calculation. Also, this estimate factors in available free or unused capacity in the existing grid and only expands where necessary. As a synthesis of these considerations, this study is using a transmission expansion cost of 0.8 MEUR/MW for nuclear power and offshore wind power and 0.4 MEUR/MW for onshore wind power and solar PV. In the least-cost mix, the installed capacities of offshore wind power and solar PV are more or less even, and a factor of 0.6 MEUR/MW is used.

In the identification of peak load productions between the alternatives, a corrected version of the installed capacities is used as shown in Table 3. Nuclear power has been reduced by 10% based on the assumption that the capacity factor in average is reduced to 90% due to maintenance. Wind power and solar PV have been reduced due to curtailment.

2.5. Grid stabilization and costs

The short-term operation of the power grid is fundamentally designed to ensure a safe and reliable electricity supply by maintaining stable frequency and voltage. Frequency is controlled by balancing an active power generation with consumption across the system, while voltage is regulated by managing the reactive power flow to keep it within a required range. In the classical power system, characterized by large synchronous generators and a predictable, unidirectional power flow from high to low voltage, this was relatively straightforward. System frequency stability was naturally supported by the inherent kinetic inertia of the rotating generators in combination with spinning reserves provided by the power plants. Voltage control, however, could not be achieved by generators alone, often necessitating additional components like capacitors and reactors.

The transition to a sustainable power system, with a rapid expansion of distributed inverter-based resources (IBRs) such as wind power, solar PV, and energy storage, marks a fundamental shift [51]. These IBRs connect via power electronics, enabling extremely fast control of both active and reactive power to dictate voltage and frequency. This changes the core dynamics of the grid from being defined by the electromagnetic physics of synchronous machines to being governed by software-based control loops within the inverters. This architecture offers significant flexibility for precise voltage control throughout the network. However, the low inherent inertia of IBRs places greater demands on communication and control systems to maintain system frequency. Furthermore, the weather-dependent nature of wind and solar generation calls for reliable forecasting tools, and the integration of storage with a well-defined state of charge enhances system balancing. This combination allows the grid to remain flexible and controllable, while still operating within the limits imposed by variable primary resources.

On one hand, the issues of grid stabilization should not be neglected – especially in the transition phase of the power system. On the other hand, future climate neutral energy systems will have sufficient units to accommodate for a proper grid stabilization without any important investments in hardware. Such units will be among others grid-connected batteries, large-scale heat pumps and electric boilers, wind turbines and PV in combination with curtailment features as well as the inclusion of storage at the plant, V2G and other types of flexible demands and peak

Table 3

Transmission system expansion costs of the individual technologies using nuclear power with the lowest costs as the benchmark.

		Nuclear	Solar PV	Onshore Wind	Offshore Wind	Least Cost Mix
Electricity demand	TWh	90.88	90.88	90.88	90.88	90.88
Installed capacity	MW	11480	150000	42890	18277	24930
Max production	MW	10332	70272	38844	11856	22064
Additional to nuclear	MW	0	59940	28512	1524	11732
Transmission system costs	MEUR/MW	0.8	0.4	0.4	0.8	0.6
Transmission CAPEX	MEUR	0	23976	11405	1219	7039
Transmission CAPEX	MEUR/year	0	1397	665	71	410
OPEX (1% af CAPEX)	MEUR/year	0	240	114	12	70
Total	MEUR/year	0	1637	779	83	481
Total	EUR/MWh	0	18.0	8.6	0.9	5.4

load gas turbines.

According to Ref. [28], the planned investments in energy plants provide ample grid stabilization capability within the system. Regarding software and operation of the units, the cost will be small and there is no reason to believe that it will deviate from one energy system to another within the comparison of this analysis. However, in the calculations, it is assumed that minor investments are needed for renewable power plants of 1% of the CAPEX, which most often would involve the inclusion of batteries and the implementation of fully featured vehicle to grid operation utilizing their capabilities. This estimate leads to investments of 3-400 MEUR equivalent to 0.3-0.4 EUR/MWh.

Alternatively, one could use synchronous compensators. An estimate based on recent investments in 2*200 MVA synchronous compensators scaled up to the scenario of the climate neutral renewable energy system leads to an investment in the same order of magnitude.

2.6. Sensitivity to electricity storage cost

The analysis of optimal combinations of storage versus overcapacities in nuclear and renewable energy sources are dominated by the fact that the CAPEX on electricity storage is high compared to other types of energy storage as well as to renewable energy sources. However, such cost relation may change in the future, and therefore a sensitivity analysis has been made with a substantially lower cost of batteries in the future.

Table 4 in the next section provides an overview. Compared to the current CAPEX on batteries, the expected cost for electricity storage in the base scenario is already low - around half of the current costs. In the sensitivity analysis, the cost of batteries is reduced further by around 50% and subsequently represents a cost corresponding to around 25% of current costs. These possible cost expectations are based on [52].

2.7. Overview cost and efficiency assumptions

Table 4 provides an overview of the most important cost assumptions. The price levels for WEO2023 and WEO2024 are expressed in real terms in USD for 2021 and 2022, respectively. The same years of price levels are valid also for the two sets of DEA prices. When the analysis was conducted and when the two WEO studies were published, the exchange rate between EUR and USD was around 1.08 USD/EUR, so cost could almost be read as USD. Currently, the exchange rate has changed.

3. Results

As further elaborated in the methodology section, LCOEs and SLCOEs have been calculated for each of the technologies in an electricity-only system representing the current situation in most countries as well as in an energy system of a future climate neutral society.

For each of the individual technologies, the calculation assumes that all electricity is produced by the individual technology in question. Afterwards, a least-cost mix is identified as a combination of all the technologies providing the least-cost solution.

With regard to the LCOE, each technology is allowed to produce electricity as fits best, i.e. wind power and solar PV as the wind blows and the sun shines, and nuclear power and CCGT in a constant high-capacity manner. For the electricity-only system, the system cost is the additional cost incurred when the technology must follow a typical hourly electricity demand profile. Here we have used a historical year of power demand for Denmark.

Fig. 3 shows the LCOE and system costs in an electricity-only system in which each of the technologies must supply all the electricity.

Using EnergyPLAN's hourly modelling, we identified the least-cost solution for each technology from the available options. As can be seen in Fig. 3, all technologies have system costs.

Using the EnergyPLAN model involves hourly simulations of all involved technologies in all sectors to accommodate for hourly representations of all demands. Thus, the simulation of, e.g., nuclear power involves back-up-power and peak-load power in order to cover all hourly electricity demands in a least-cost manner. In the specific case of nuclear power in the climate-neutral system, peak-load power capacity is 3100 MW, while back-up is accommodated in a joint partnership between the peak-load and the nuclear plants. For wind and solar PV, the need for peak-load and back-up is higher.

Nuclear power and CCGT require overcapacity (and therefore lower capacity factors) to cover peaks. However, for none of these technologies is it feasible to use electricity storage because of the high costs. For nuclear power, the system costs are higher than for CCGT because the CAPEX is substantially higher.

For solar PV and wind power, the least-cost solution is to be found in a combination of increasing the capacity of the technology itself and investing in electricity storage. Thus, the electricity storage covers the hours in which the solar PV and the wind power cannot supply enough including peak load.

A least-cost combination of all the technologies has also been identified (shown in Fig. 3 as Least Cost Mix). Under the IEA/WEO 2023 cost assumptions, the least-cost solution comprises a combination of offshore wind power (66%), solar PV (8%) and CCGT (26%). Onshore wind power cannot compete with offshore wind power, and nuclear power cannot compete with any of the other technologies. This is due to the relatively low offshore and high onshore wind power cost assumptions in WEO 2023. As we shall see later, onshore wind power comes into the least-cost mix when using WEO 2024 or any of the two DEA cost assumptions.

It should be mentioned that while nuclear power, solar PV and wind power are all climate neutral and use no biomass, CCGT and therefore also the least-cost mix either use natural gas or biomethane. Therefore, we have also included a least-cost mix with a biomass restriction. The biomass restriction refers to a climate neutral society based on the use of sustainable biomass only. Such an alternative is described in detail in Ref. [23].

The “LC mix biomass restricted” alternative is still comprised by a least-cost combination of offshore wind power (84%), solar PV (13%) and CCGT (3%), however with a minor CCGT production. In this

Table 4
Investment cost, technical lifetime, fixed and variable O&M and technical data for essential technologies of this analysis.

Nuclear	CAPEX [M€/MW)	interest rate [%]	Technical lifetime [years]	Fixed OPEX [percent of investment]	Variable OPEX [€/MWh]	Capacity factor	Total per unit cost **** [€/MWh]	Source
Nuclear WEO2023	6.50	8	60	3.77	Incl. in fixed	0.80	110	[34]
Nuclear WEO2024	7.30	8	60	3,15	Incl. in fixed	0.75	125	[35]
Sensitivity analysis	6.50	5	60	3.77	Incl. in fixed	0.80	85	

Nuclear (Input EnergyPLAN)	*CAPEX [M€/MW)*	*interest rate [%]*	*Technical lifetime [years]*	*Fixed OPEX [percent of investment]*	*Variable OPEX [€/MWh]*	*Capacity factor*	*Total per unit cost ****[€/MWh]*	*Source*
Nuclear WEO2023	*10*	*5*	*60*	*2,45*	*Incl. in fixed*	*0.80*	*110*	[34]
Nuclear WEO2024	*11.2*	*5*	*60*	*2,05*	*Incl. in fixed*	*0.75*	*125*	[35]
Sensitivity analysis	*6.50*	*5*	*60*	*3.77*	*Incl. in fixed*	*0.80*	*85*	

Renewable Energy Sources (WEO2023)	CAPEX [M€/MW)	Technical lifetime [years]	Fixed OPEX [percent of investment]	Variable OPEX [€/MWh]	Capacity factor	Total per unit cost ****) [€/MWh]	Source
Wind: large-scale onshore 2050	1.61	30	2.45	Incl. in fixed	0.30	55	[34]
Wind: large-scale offshore 2050	1.95	30	2.65	Incl. in fixed	0.59	35	[34]
Solar PV: 2050	0.48	30	2.56	Incl. in fixed	0.14	35	[34]

Renewable Energy Sources (WEO2024)	CAPEX [M€/MW)	Technical lifetime [years]	Fixed OPEX [percent of investment]	Variable OPEX [€/MWh]	Capacity factor	Total per unit cost **** [€/MWh]	Source
Wind: large-scale onshore 2050	0,78	30	3,37	Incl. in fixed	0.30	25	[35]
Wind: large-scale offshore 2050	1.85	30	2,65	Incl. in fixed	0.56	35	[35]
Solar PV: 2050	0.35	30	3,50	Incl. in fixed	0.14	25	[35]

Renewable Energy Sources (DEA2020)	CAPEX [M€/MW)	Technical lifetime [years]	Fixed OPEX [percent of investment]	Variable OPEX [€/MWh]	Capacity factor	Total per unit cost **** [€/MWh]	Source
Wind: large-scale onshore 2035	1.14	30	2.07	Incl. in fixed	0.37	30	[53]
Wind: large-scale offshore 2035	1.76	30	3.15	Incl. in fixed	0.51	38	[53]
PV: large-scale rooftop 2035	0.53	40	1.63	Incl. in fixed	0.14	32	[53]

Renewable Energy Sources (DEA2025) ((DEA2020 plus 50% on capex and plus 20% on OPEX)	CAPEX [M€/MW)	Technical lifetime [years]	Fixed OPEX [percent of investment]	Variable OPEX [€/MWh]	Capacity factor	Total per unit cost **** [€/MWh]	Source
Wind: large-scale onshore 2035	1.71	30	1.66	Incl. in fixed	0.37	43	
Wind: large-scale offshore 2035	2.64	30	2.52	Incl. in fixed	0.51	53	[53]
PV: large-scale rooftop 2035	0.80	40	1.30	Incl. in fixed	0.14	46	

Energy Conversion technologies	Investment Cost [M€/MW]	Technical lifetime [years]	Fixed O&M [percent of investment]	Variable O&M [€/MWh-e]	Efficiency Electric Output [percent]	Efficiency Thermal output [percent]	Source
Small CHP plants 2035	0.94	25	1.03	3.36	50	48	[53,54]
Large CC CHP plants 2035	0.76	25	3.33	3.36	53	34	[53,54]
Large Power plants 2035	0.58	25	3.35	2.92	45-56	-	[53,54]
Large DH Heat Pumps 2035	2.32	25	0.52	0.43		390 (COP)	[53,54]
Electrolysis 2035	0.56	25	6.00	Incl. in fixed	Hydrogen output: 65	15	[55] [a])

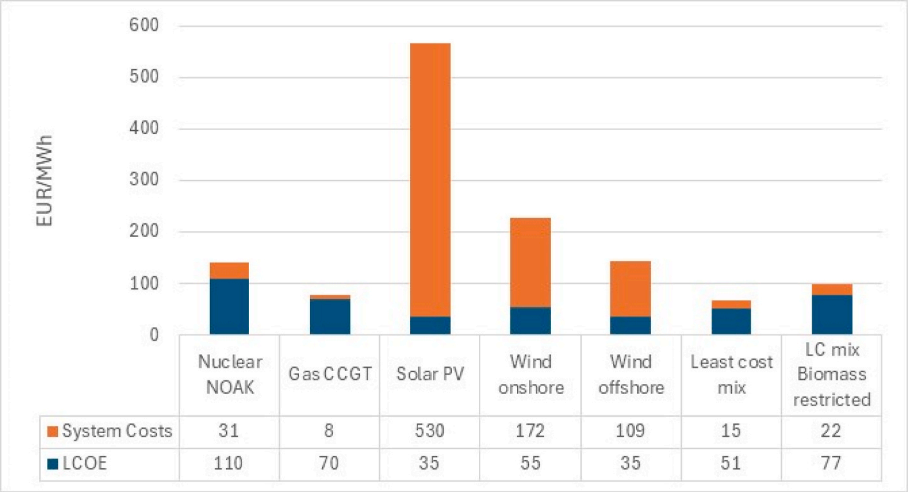
Energy Storage Technologies	Investment Cost [M€/GWh)	Technical lifetime [years]	Fixed O&M [percent of investment]	Variable O&M [€/MWh]	Cycle efficiency	Annual costs d [€/MWh storage capacity]	Source
Electricity storage	175	50	0.5	1.19	0.85	7700	[56]
Thermal pit storage (solar)	0.5	25	0.59	Incl. in fixed	0.95	30	[55]
Thermal large tanks storage	3	40	0.29	Incl. in fixed	1		[55]
Thermal storage for DH	*2*	*35*	*0.4*	*Incl. in fixed*	*1*	*100*	b
Cavern hydrogen storage	3	30	5	Incl. in fixed	1	300	[55]
Large steel tank hydrogen	75	30	2	Incl. in fixed	1	5300	[55]
Hydrogen storage	*3*	*30*	*5*	*Incl. in fixed*		*2700*	c
Gas (Methane) storage	0.06	50	0.5		0.98	3	[56]
Liquid (methanol) storage	0.02	30	0.5		1	1	[56]

Electricity Storage Technologies cost sensitivities	Investment Cost [M€/GWh)	Technical lifetime [years]	Fixed O&M [percent of investment]	Variable O&M [€/MWh]	Cycle efficiency	Annual costs [€/MWh storage capacity]	Source
Electricity storage	175	50	0.5	1.19	0.85	7700	[56]
Battery (current in DK)	145	15	1.3	Incl. in fixed	0.88	14000	e
Battery (expected EU future)	40	20	2.5	Incl. in fixed	0,85	3700	

[a] assuming a combination of Alkaline, PEM and SOEC electrolysis technologies.

[b] For seasonal thermal storage for solar thermal is used "Thermal pit" and for thermal storage in district heating systems a combination of 40% "pit" and 60% "large tank" is used.

[c] For hydrogen storage the cost of caverns is used since this is likely the marginal costs of having a little more or a little less capacity.
[d] Calculated based on an interest rate of 8 percent for nuclear and 5 percent for renewable energy.
[e] Personal communication with Danish project developer.



	Nuclear NOAK	Gas CCGT	Solar PV	Wind onshore	Wind offshore	Least cost mix	LC mix Biomass restricted
🟧 System Costs	31	8	530	172	109	15	22
🟦 LCOE	110	70	35	55	35	51	77

Fig. 3. LCOE (blue) and system costs (orange) (together SLCOE) for individual technologies in an electricity supply only system. As detailed in Fig. 4, system costs are comprised by overcapacity of the technology itself, electrolysers and hydrogen storage, back-up power, influence on spinning reserve and transmission systems cost.

situation, nuclear power cannot compete with the other technologies, either.

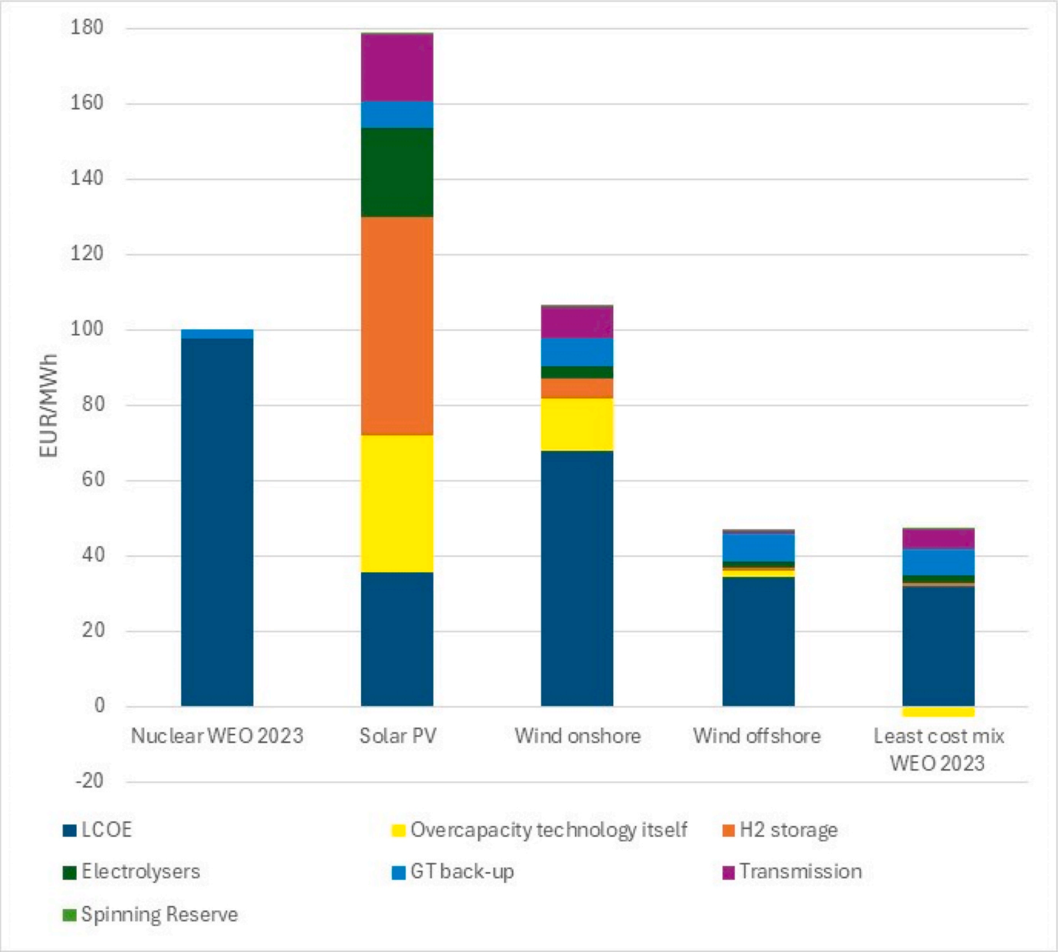


Fig. 4. LCOE (blue) and system costs (remaining colours) (together SLCOE) for individual technologies in a future integrated energy system of a climate neutral society (top) and specifications of the system costs using nuclear power as the benchmark (bottom).

Fig. 4 shows the same, in the case of an energy system in a climate neutral society. As can be seen, the system cost of each technology in the climate neutral system is significantly lower than in the electricity-only system. This is due to the many new and better integration options.

No matter how the electricity is produced, this system has a high flexibility from among others the smart charging of electric vehicles, the smart operation of heat pumps and electric boilers and the smart operation of Power-to-X and electrolysers. Thus, the system costs of nuclear power are rather small and mainly arise from the need for back-up power.

However, a solution based solely on solar PV results in substantial system costs in both energy system contexts. The role of solar PV is to be used in combination with wind power (or other solutions) and thus contributes to lowering the total cost of a least-cost combination of technologies.

It should be emphasized that all the alternatives have exactly the same use of biomass and they all contribute with carbon for CCU, CCS and biochar to achieve a fully climate neutral society in all sectors including agriculture, industrial processes and LULUCF.

In the alternatives of the climate neutral society, the CCGT technology has been excluded, since it will not be feasible within the limits of sustainable biomass. However, all alternatives include back-up capacity of gas turbines (OCGT) and compensation for the use of these by other measures, which means that the limit of sustainable biomass is fulfilled in all alternatives.

Again, the least-cost mix is composed solely of offshore wind power and solar PV. Onshore wind power cannot compete with offshore wind power, and nuclear power cannot compete with suitable combinations of RES technologies.

This structural finding is confirmed by a recent energy system analysis on the case of Finland [44] to find attractive energy system solutions with new nuclear power investments, including SMRs also in CHP mode, and with low cost of capital. However, the energy system costs with growing shares of nuclear power have been considerably higher than in the reference system without any new nuclear power investments.

3.1. Sensitivity analysis

Three sensitivity analyses have been conducted. The first concerns

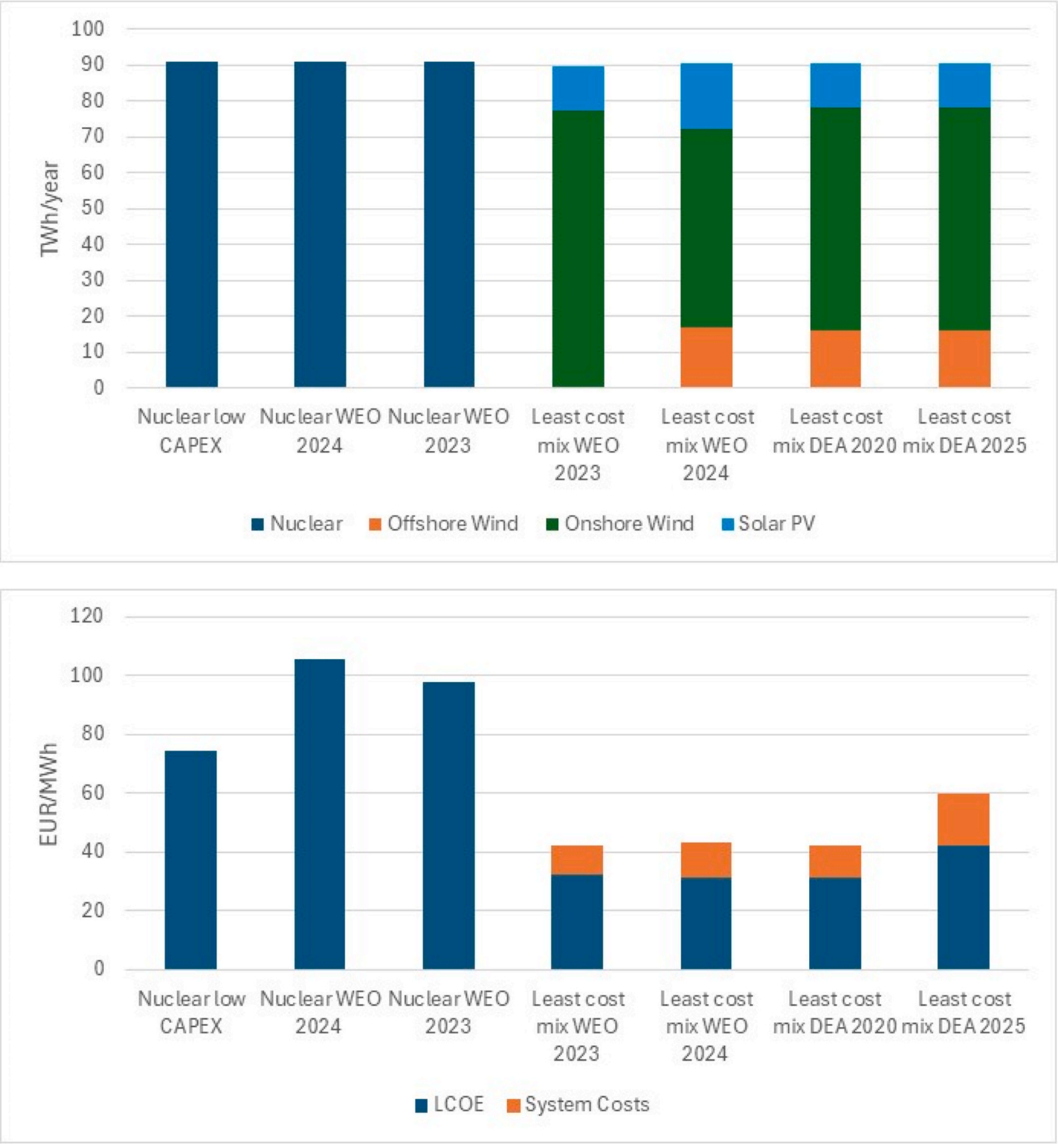


Fig. 5. Sensitivity analysis of LCOE and system costs (together SLCOE) in a future integrated energy system of a climate neutral society with different costs and capacity factor assumptions.

the costs of nuclear and RES technologies. The next concentrates on the cost of the flexibility measures to balance supply and demand, while the third focuses on the cost of the electricity storage capacity. Fig. 5 shows the least-cost solutions for the future climate neutral society with alternative costs and efficiency assumptions as described in detail in the methodology section.

The sensitivity analysis of Fig. 5 focuses on the costs of nuclear power and renewable energy technologies. However, also the cost of the system technologies providing flexibility has an influence. Fig. 6 shows the results of a sensitivity analysis of 50% increases in the CAPEX on these technologies.

As can be seen from Fig. 6, changes in the cost of flexible technologies have little influence on the results.

As can be seen from the results in Fig. 5, the least-cost combination of solar PV and onshore and offshore wind power differs between the different cost and capacity factor assumptions of WEO and DEA.

However, with regard to LCOE and SLCOE, the results are robust and provide the following conclusions.

- The costs are highly dependent on the context of the system. Thus, in a future energy system of a climate neutral society, the system costs of renewable energy are quite different from the system costs of an electricity-only system.
- In a future energy system in a climate neutral society, the system costs of renewable energy compared with nuclear power are small compared to the differences in LCOE.
- Different cost assumptions between WEO and DEA may influence the least-cost combination of solar PV, onshore and offshore wind power, but do not make much of a change with regard to system costs and SLCOE.
- In all alternatives, the costs of RES including system cost are significantly lower than the costs of nuclear power.

The final sensitivity analysis concentrates on the electricity storage cost. As detailed in the methodology section and Table 4, the main analysis assumes future electricity cost to be around half of the current costs of battery storage. However, the cost of batteries is expected to decrease. In the sensitivity analysis, a further 50% cost reduction is assumed as explained in Table 4.

The results are shown in Figs. 7 and 8, which can be compared to Figs. 3 and 4.

In general, cost reductions in electricity storage lead to lower overall costs since new and more optimal combinations of power production capacities and flexibility can be found in several of the cases.

Especially for the wind and solar power alternatives, better solutions can be found, in particular in the context of an electricity-only system.

In the context of a climate neutral society based on a smart sector integrated energy system, the effect of lower electricity storage cost is marginal or negligible. This is caused by the fact that such systems already utilize more affordable options of flexibility, as already explained.

4. Conclusion and discussion

This study generates conclusions at the general theoretical level as well as the specific case level.

At the theoretical level, it is found that LCOE does not capture all costs which are relevant for comparing different technologies. The system costs must be included. Here, we introduce a system-based LCOE, referred to as a SLCOE. While the LCOE is a function of the technology

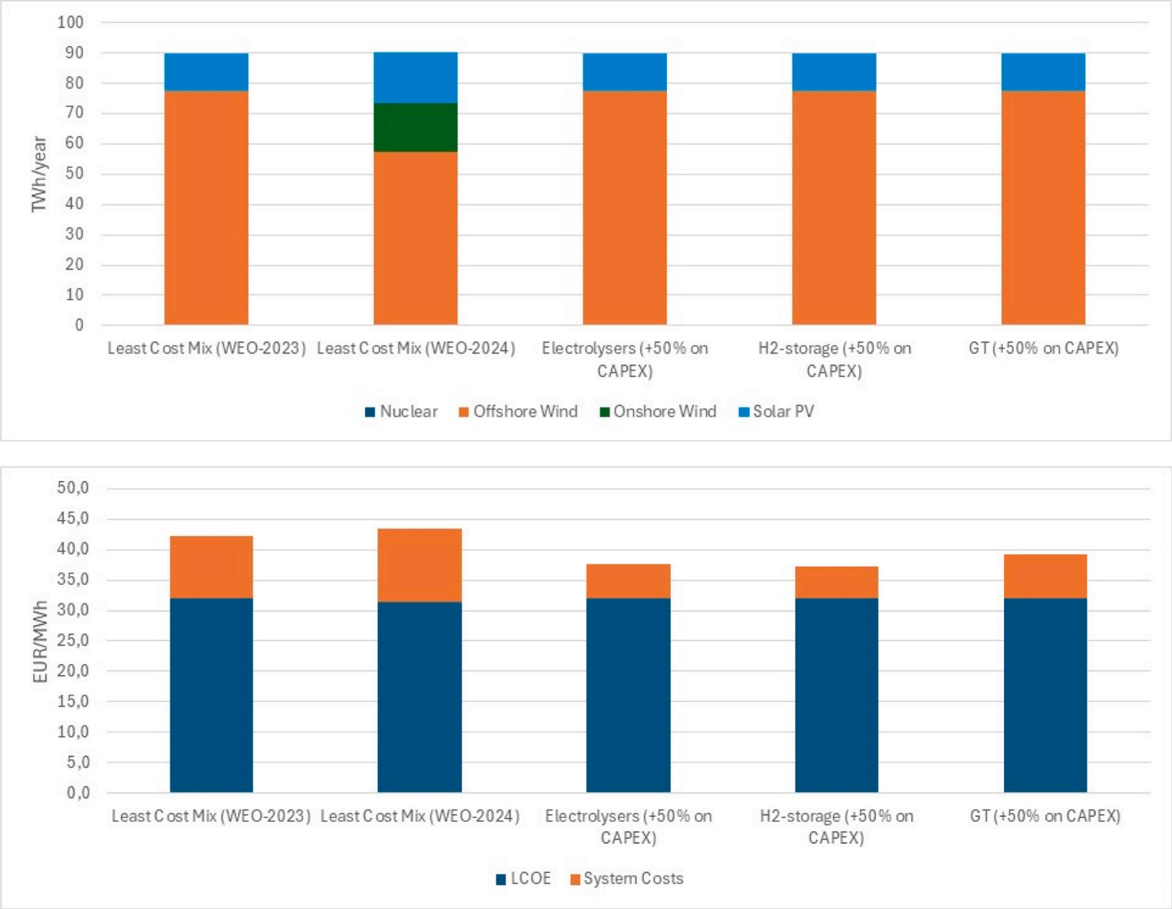


Fig. 6. Sensitivity analysis of changes in the cost of technologies providing flexibility in the integration of renewable energy.

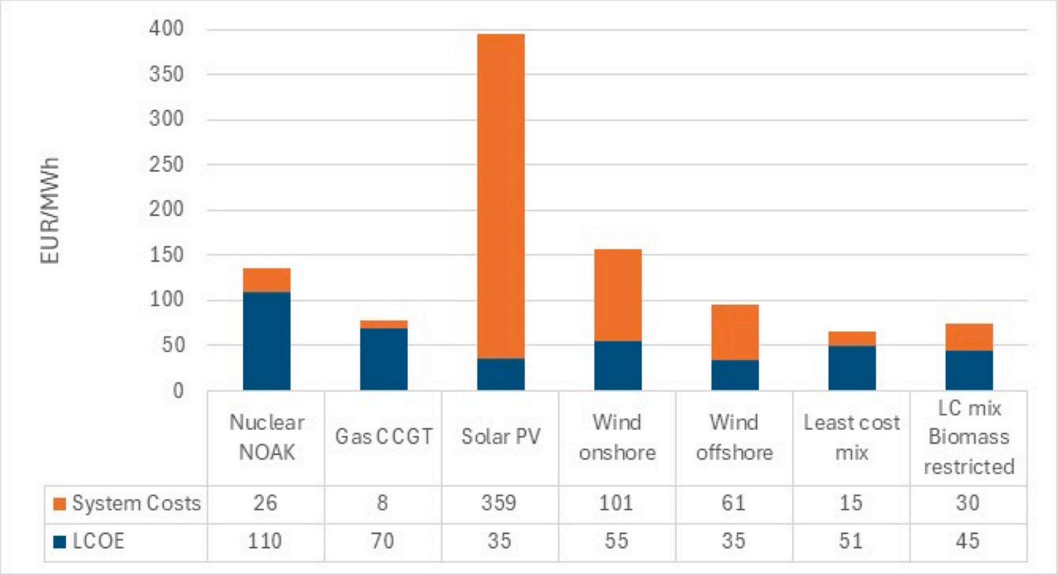


Fig. 7. Sensitivity analysis. LCOE and system costs (together SLCOE) for individual technologies in an electricity supply only system with reduced electricity storage costs. The figure is parallel to Fig. 3 above.

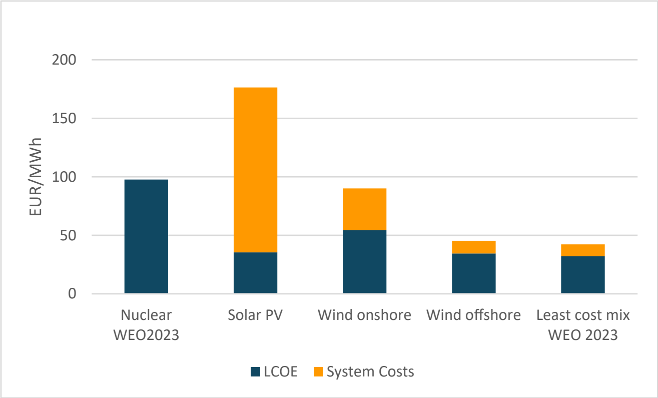


Fig. 8. Sensitivity analysis: LCOE and system costs (together SLCOE) for individual technologies in a future integrated energy system of a climate neutral society with reduced electricity storage costs. The figure is parallel to Fig. 4 (top) above.

itself, the SLCOE is a function of both the technology and the energy system context in which the technology operates.

Based on IEA/WEO and DEA cost assumptions, we identify LCOE and SLCOE for nuclear power, solar PV, offshore and onshore wind power in Europe. Moreover, we identify least-cost combinations of these technologies. Using Denmark as a case, we compare these costs of the energy system of today with the future energy system of a climate neutral society. All technologies are compared using detailed hourly modelling and under the same biomass restriction, and system costs include investments in flexibility, back-up power, grid stabilization and balancing as well as transmission.

At the theoretical level, we find that the system costs of nuclear power and of RES such as wind power and solar PV are high in the electricity supply system of today. However, they are all much lower in an energy system of a future climate neutral society, because such future systems involve a high proportion of new cross-sectoral flexible electricity demand, which allows for much more affordable solutions.

Single-technology solutions in which one technology (nuclear power, solar PV or wind power) supplies all electricity of the entire system have high system costs. The best solutions are to be found in the combination of more than one technology.

At the case level, we find that in countries such as Denmark with available wind and solar energy resources, nuclear power does not seem to be part of the least-cost solution, neither in today's energy systems nor in future systems of climate neutral societies. This conclusion is valid for the present cost of nuclear power in Europe as well as for IEA/WEO future expectations. The future overnight cost for nuclear power of 4500 EUR/MW in 2050 represents the so-called “nth-of-a-kind” cost for new reactor designs, with assumed substantial cost reductions from the first-of-a-kind projects, while this violates the historical experience of nuclear power technology.

The modelling performed at the case level does not include every aspect. E.g., we have not included the additional costs of establishing authorities and storage facilities for high-radioactive waste in a country that has not had nuclear power before or opportunity costs related to the planning and building of nuclear power, which take much longer than for renewable energy. The inclusion of such aspects will confirm the above conclusion.

Even when not including these aspects, the sensitivity analyses show that the results are robust to substantial changes in CAPEX, such as a 50% increase in wind power and solar PV, as well as the technologies providing system flexibility.

In this study, we have not modelled in detail the need for back-up power in the case of uncertainties such as fall-out and maintenance of nuclear power. Nor have we intended to model differences in wind power and solar PV between specific years. These are case-specific issues relevant for future studies, but they do not affect the overall methodological approach as presented in this study.

CRediT authorship contribution statement

Henrik Lund: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Jakob Zinck Thellufsen:** Writing – original draft, Validation, Data curation, Conceptualization. **Poul Alberg Østergaard:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Christian Breyer:** Writing – review & editing, Data curation, Conceptualization. **Neven Duic:** Writing – review & editing, Conceptualization. **Frede Blaabjerg:** Writing – original draft, Data curation, Conceptualization. **Aoife Foley:** Writing – review & editing, Conceptualization. **Jacob Østergaard:** Writing – review & editing, Conceptualization. **Meng Yuan:** Writing – review & editing, Conceptualization. **Poul Thøis Madsen:** Writing – review & editing. **Brian Vad Mathiesen:** Writing – review & editing, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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