Cost and system effects of nuclear power in carbon-neutral energy systems

Thellufsen, Jakob Zinck; Lund, Henrik; Mathiesen, Brian Vad; Østergaard, Poul Alberg; Sorknæs, Peter; Nielsen, Steffen; Madsen, Poul Thøis; Andresen, Gorm Bruun

Published in:
Applied Energy

DOI (link to publication from Publisher):
10.1016/j.apenergy.2024.123705

Publication date:
2024

Document Version
Publisher's PDF, also known as Version of record

Applied Energy 371 (2024) 123705

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Cost and system effects of nuclear power in carbon-neutral energy systems

Jakob Zinck Thellufsen [a,*], Henrik Lund [a], Brian Vad Mathiesen [b], Poul Alberg Østergaard [a], Peter Sorknæs [a], Steffen Nielsen [a], Poul Thøis Madsen [a], Gorm Bruun Andresen [c]

[a] Department of Sustainability and Planning, Aalborg University, Rendsburggade 14, 9000 Aalborg, Denmark
[b] Department of Sustainability and Planning, Aalborg University, A.C. Meyers Vænge 15, 2450 Copenhagen, Denmark
[c] Department of Mechanical and Production Engineering, Aarhus University, Inge Lehmanns Gade 10, 8000 Aarhus, Denmark

HIGHLIGHTS

- Both renewable energy and nuclear power benefits from sector coupling.
- Hourly modelling is required to capture system effects.
- Nuclear systems require less flexibility capacity than renewable only systems.
- A renewable energy system is cheaper than a nuclear based system.
- Lower flexibility costs do not offset the high investment costs in nuclear energy.

ARTICLE INFO

Keywords:
Energy system analysis
Carbon neutral energy systems
Nuclear power
Renewable energy
Carbon neutrality
EnergyPLAN

ABSTRACT

Moving towards carbon-neutral societies, both nuclear and renewable energy can potentially supply CO_2-free electricity. While the cost of renewable energy has decreased significantly, the cost of nuclear has, however, increased in the past decades and now in general exceeds the cost of renewables. However, one cannot compare directly the per unit cost of electricity since temporal behavior in the electricity production differs substantially between the two groups of technologies. Nuclear power inherently aims to provide a constant base load supply of electricity, while renewables generally depend on weather patterns. Thus, the two have different requirements and impact the overall system costs differently regarding flexibility and system design. Focusing on the case of Denmark, this article investigates a future fully sector-coupled energy system in a carbon-neutral society and compares the operation and costs of renewables and nuclear-based energy systems. The study finds that investments in flexibility in the electricity supply are needed in both systems due to the constant production pattern of nuclear and the variability of renewable energy sources. However, the scenario with high nuclear implementation is 1.2 billion EUR more expensive annually compared to a scenario only based on renewables, with all systems completely balancing supply and demand across all energy sectors in every hour. For nuclear power to be cost competitive with renewables an investment cost of 1.55 MEUR/MW must be achieved, which is substantially below any cost projection for nuclear power.

1. Introduction

With the transition towards providing fossil free, zero carbon emission energy, national energy systems will have to change. Research points to electrification and sector-coupling as the most promising pathways [1], as it allows the utilization of carbon free energy sources,[1] such as wind power and nuclear power, in sectors traditionally relying on fossil fuels. This includes for instance the use of electric vehicles instead of internal combustion engine-based vehicles [2,3] and the use of electric boilers and heat pumps in industry [4,5] and households [6,7]. In sectors that are difficult to electrify directly, power-to-X technology are typically proposed to allow indirect electrification through the production of synthetic fuels such as hydrogen, methanol, and ammonia [8,9]. Furthermore, sector coupling also allows for increased

* Corresponding author.
E-mail address: jakobzt@plan.aau.dk (J.Z. Thellufsen).

[1] In this article, we only address emissions from the operation stage and thus not life-cycle carbon emissions.

https://doi.org/10.1016/j.apenergy.2024.123705
Received 10 January 2024; Received in revised form 10 June 2024; Accepted 11 June 2024
Available online 17 June 2024

energy efficiency using, for instance, excess heat from industrial processes to provide space heating for dwellings through district heating systems [10,11]. A fully sector-coupled energy system has also been labelled a smart energy system [12,13]. In essence, an energy transition based on a smart energy approach would enable the use of carbon-free electricity and heat to supply a more efficient energy system, where most of the required flexibility can be established through demand and supply flexibility [14,15] and low-cost storage outside the electricity system, such as thermal storage, hydrogen storage and gas/fuel storages [16].

Most research investigating how such energy systems can provide a clean and green transition, points to the use of renewable energy sources (RES), as RES provides both cost efficiency and zero carbon emissions. Examples of such research on a European level rely on various energy modelling platforms, including PyPSA [17,18], Calliope [19], EnergyPLAN [1], Balmorel [20] and TIMES [21]. Furthermore, several studies have shown that RES in a smart energy system can provide the needed energy to fulfill all energy demands in every hour of a year, and by using sector coupling avoid a significant overbuild of the system [1,13,16,17,22,23]. In [14] it is possible to achieve a 100% renewable energy scenario for Denmark, with 10 GW PV, which potentially can be located on rooftops, 5 GW onshore wind, which is only slightly higher than the current 4.3 GW and with the remaining 14 GW renewable capacity being offshore wind power.

Nuclear power produces steam, which most often is utilized to provide carbon-free electricity [24] and does, thus, potentially constitute an alternative or supplement to RES in a carbon-neutral energy system. However, in recent years the cost of nuclear power plants has increased significantly, making it hard for the plants to compete with cheaper RES [25]. Furthermore, several nuclear projects have seen significant cost overruns [26,27]. Cost projections of future nuclear plants, and costs of nuclear technologies not yet developed do however suggest lower costs than those built currently according to some sources [28].

Nuclear power has therefore been attracting some interest recently, despite the high degree of cost uncertainty [29]. In a 2022 report, the International Energy Agency ask the question whether there is a new dawn for nuclear energy [30], answering by stating that it has the ability to assist the transition away from fossil fuels. The International Atomic Energy Agency [31] also expresses that nuclear can assist RES but also that there are challenges regarding business cases and profitability options.

Compared to variable RES, there are system benefits of nuclear power, which must be assessed to give a full picture of nuclear power's potential role in a transition towards carbon neutral energy systems. The IEA has considered this benefit based on value-adjusted levelized cost of energy (VALCOE) [28,32]. However, these are not based on full-fledged energy system analyses, but instead on an assessment of the flexibility and stability of each technology in isolation.

Some newer review articles on hybrid nuclear RES-based systems, e.g. [33,34] address challenges and opportunities of this solution, but they do not focus on the character of any underlaying systems analyses. For the evaluation of different potential energy futures, however, energy system analyses are required to assess the possible role of nuclear in competition with other carbon-neutral technologies. Also, several studies do include nuclear in an energy system analysis [35–40], but not all are explicitly discussing nuclear in comparison to RES. Below, we address a few of these studies.

In [35], Kan, Hedenus and Reichenberg investigate the economic rationale for Sweden to reinvest in nuclear power with a primary focus on the electricity system and without extensive sector coupling. They conclude that the economic rationale is limited.

In a TIMES model for France [38], the Business-as-Usual scenario with no restriction on nuclear expansion is the cheapest energy system. However, this study is not based on high-temporal resolution simulations like hourly analysis, and, to the best of our knowledge, there is no evaluation or documentation of assumptions for costs of any technologies. Also, the Business-as-Usual scenario with high levels of nuclear is depending on income from the export of excess electricity.

Pfenninger and Keirstad [40] identify that nuclear and renewable energy cost the same for a transition in the United Kingdom energy system, but the investigated systems do not consider sector coupling. Furthermore, significant cost reductions of RES have been realized since the publication of the paper in 2015. Similar critical cost assumptions are found in [36,41], which highlights the need for updating the literature.

Fattahi et al. [42] present analyses of the techno-economic role of nuclear power in the Dutch energy transition. This study uses the IESA-Opt-N optimization model and compares a scenario with no nuclear allowed with a scenario where nuclear is allowed. It finds no significant differences in the total costs between the systems, however, the scenario with nuclear provides lower electricity prices for the consumer. However, this conclusion is not reached by comparing with a system based on renewable energy. In both systems, with and without nuclear, the maximum renewable capacity potential is reached (12 GW onshore wind e.g.). While there are limits to renewable build out capacities, the ENSPRESO studies show that it is potentially higher than 12 GW onshore [43] in NL. Furthermore, and more important, the fact that it is maxed out in all scenarios, has the consequences that Fattahi et al. in effect studies and compares nuclear buildout to importing electricity at 115 EUR/MWh. In this case nuclear is a credible option, but if electricity prices are to drop, the model does not invest in additional nuclear power. For the Generation III nuclear power station, the authors assume base-load operation with a capacity factor of 90%. This is high compared to [28], where a 2050 capacity factor of nuclear power in the European system of 70–80% is projected due to large expansion of RES requiring part-loading in nuclear power stations. However, the capacity factor, should be investigated as part of the system operation. Furthermore, Fattahi et al. do not utilize system benefits and direct electrification to its fullest, exemplified by using hydrogen boilers for heating, which results in an inefficient energy system.

Cárdenas et al. [44] analyze the effect of nuclear power in a future energy system in the United Kingdom. The article focuses on baseload operation of nuclear power, at different levels of nuclear and renewable energy penetration and on balancing the electricity sector with different types of energy storages. With current nuclear costs, the study finds that no nuclear power will be needed in the future energy system, but also finds that cost reductions within nuclear power would lead to higher penetrations of nuclear power. However, the study does not cover the entire energy system, and therefore leaves out potential system benefits from sector coupling.

In a recent study [45], Duan, Petroski, Wood and Caldeira investigate a flexible nuclear plant using a thermal energy storage to maintain fixed operation on the reactor but flexible electricity production to complement or substitute RES in a number of countries around the world. The study also includes natural gas power stations with Carbon Capture and Storage and batteries as additional sources of carbon-neutral flexibility. However, the study completely neglects all other technologies and energy needs beyond existing demand for electricity. The study finds that nuclear is the cheapest option for decarbonization levels beyond about 80%, a result which is unsurprising giving the uncommonly high-cost assumptions for solar and batteries in particular and the lack cheaper flexibility measures from sector integration, as discussed in [16].

Bryan et al. [46] analysed an electricity supply system for Texas, finding an optimum based mainly on nuclear power and to a lesser extent on photo voltaics (PV) and wind power. This analysis is based on a capacity factor of 90% for nuclear power and electrolysis, hydrogen storage and fuels cells for supplementary production. More economical flexibility measures, such as system integration and the use of hydrogen in fuel production, in the wider energy system are thus not explored.

Romanos et al. [47] investigate the combination of nuclear power and thermal energy storage, storing electricity as heat in off-peak hours, to be used, through a Rankine cycle power plant in high-demand periods. More specifically, a flexible organic Rankine cycle-based system, combined with thermal storage in phase change materials, is investigated and compared to an existing steam-based system. The paper studies the economic profitability of such implementation and arrives at the finding that under the conditions that price variations at least double compared to 2019, and multiple operation cycles during the day or long discharge times occur, a positive net present value can be achieved. However, the study does not engage in a wider system analysis, and the lowest identified levelized cost of electricity (LCOE) of 159 GBP/MWh from the thermal-based electricity storage, suggests a need for system analysis, as other flexibility measures exist. Other studies have investigated the role of Carnot batteries (thermal energy storage) using a wider system perspective, such as Nitsch et al. [48] and Sorknæs et al. [49]. The findings of Sorknæs et al. [49] indicate that the operation of such storages should aim for an LCOE of lower than 66 EUR/MWh to compete with other flexibility measures.

Al Kindi et al. [50] and Aunedi et al. [51] also investigate the combination of nuclear power and thermal energy storage, including an energy system analysis. They find a similar conclusion, i.e. that thermal energy storage can improve the economy of nuclear power and the entire energy system, by allowing for more constant operation of the nuclear power station in systems dominated by renewable energy. The papers include scenarios where the nuclear capacity is exogenously determined to be either one or five 1600 MW plants, and investment costs are not considered. Therefore, the studies discuss how to improve the feasibility of existing nuclear power and not whether nuclear power is competitive with renewable energy.

Masotti et al. [52] investigated different combinations of nuclear and RES combined with hydrogen for the supply of electricity and other energy carriers using a Modelica-based model. However, there was focus on technical characteristics of the system and no focus on the economic viability of the solutions. Similarly, Gerkšič et al. [53] investigates whether nuclear power could assist PV in the Slovenian system, and while their simulations showed prospects, the analyses were based on technical feasibility only.

Qu and Bang [54] investigated small modular reactors with wind power from a business-economic investment perspective. The analyses were thus not based on holistic energy systems simulations. Their analyses suggested that *"increasing feed-in premium on nuclear energy is the most effective way, although it may require high government budgets"* for the small modular reactors to become competitive with offshore or onshore wind power.

There is also reasonable body of literature on nuclear / hydrogen systems, e.g. [55–59] however typically seen apart from the rest of the energy systems, and thus of a limited scope.

Based on the literature, we find that there is a significant gap in the current academic literature on the co-existence of RES and nuclear energy. There are studies addressing parts of the energy system, there are studies focusing on the economics of the combination and there are studies focusing on technical prospects of nuclear RES combinations. We have found only limited journal literature on combining these three elements. Also, we have not identified studies where all energy demands are included and flexibility arising from the electrification and sector coupling across all sectors are utilized. Furthermore, there is a need for additional studies using updated cost assumptions and technology-rich models.

With the identified gaps in the literature in mind, the goal of this study is to assess nuclear power and compare it to RES under the circumstances of providing energy to a fully decarbonized and fossil free energy system. The study considers that nuclear power is typically a constant-producing power source, and thus, pose different flexibility requirements to energy system than RES which is weather dependent. Furthermore, the study ensures that all energy demands are equal independent of nuclear and RES capacity meaning that each scenario covers the same electricity, industry, transport and heating demands, allowing for a clearer comparison. Finally, the study utilizes sector coupling across sectors. In total this ensures the systems are comparable in terms of the same parameters.

By including temporal production and demand patterns in energy system analyses, including changes in energy system flexibility and impacts on overall costs of the total energy system, this study intends to provide a clear perspective of the competition between RES and nuclear power in decarbonizing the energy system. The paper conducts the analysis using a smart energy system scenario for Denmark in 2045, but the methodology can be applied to different national cases as well, taking into consideration specific circumstances in constraints and costs depending on the case.

The novelty of the paper lies in its full-fledged techno-economic energy system analysis and comparison of energy systems based on combinations of nuclear power and RES. The importance of the work is supported by the renewed interest in nuclear options by, e.g., the IEA and clearly by the decarbonization effort laying ahead of all societies.

The paper treats nuclear power as a principal technology type, and therefore does not go into the discussion between small modular reactors [60] and larger conventional reactors. Current levelized cost of electricity (LCOE) [28] costs for any nuclear technology indicate that regardless of the nuclear power station being conventional or SMR [61], the desired operation strategy will be to maximize operation hours and achieve the highest capacity factor possible [62]. Furthermore, a recent study [29] suggests that SMR might not achieve lower LCOE than conventional nuclear.

In Section 2, we present the methods applied for systems analyses and scenarios design, with the scenario is presented in Section 3. Results from the systems analyses are presented in Section 4, and finally Section 5 draws the main conclusions.

2. Methods

To investigate and compare renewable and nuclear-based energy system designs, an analysis covering all sectors and all hours of the year is crucial. This section covers three key-areas. The first subsection describes the overall energy system layout and more importantly the associated energy demands. The second subsection describes cost assumptions and a technology overview of renewable energy and nuclear power. The final subsection details how the chosen energy systems simulation tool EnergyPLAN handles the analyses as well as how each technology is modelled.

2.1. Smart energy Denmark and energy demand

To analyze the required electricity capacity and production in a carbon-neutral energy system, it is important to identify future energy demands. These demands include electricity demands, heating and cooling demands, industrial demands, and transport demands. In future energy systems most of these demands are expected to be covered by direct electrification [63]. For some demands, like heating, waste energy from various processes can be used, and for demands not suitable for direct electrification, such as certain industry and transport demands, hydrogen from electrolysis and electrofuels are currently the suggested solution [64]. Both hydrogen and electrofuels require electricity as their main input [8].

The scenario allows for an electric interconnection to the surrounding countries but only with a maximum capacity of 6 GW and that it must balance import with CO_2-neutral exports. Furthermore, the exchange is constrained, simulating that the import and export must balance through an external storage of 820 GWh. In comparison Norway, which Denmark is connected to, has a total hydro storage capacity of 87 TWh [65]. This ensures the CO_2-neutrality of the imports and exports.

The energy demands In this study comes from recent Smart Energy Denmark [14] scenario from "IDA's Climate Response" [66]. This highlights a renewable energy scenario for Denmark, and functions as the scenario detailing an energy system without nuclear, as it is mostly

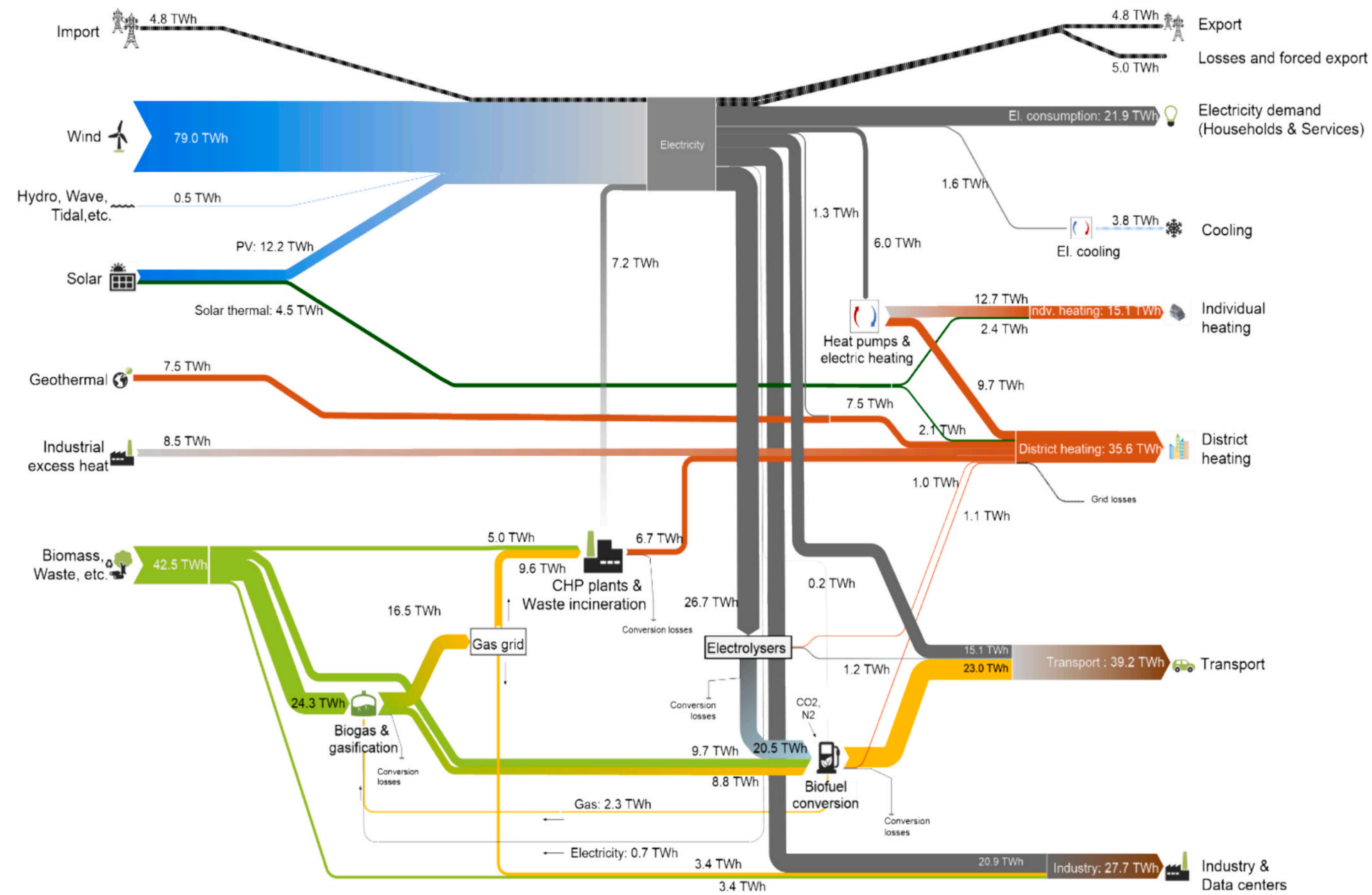

Fig. 1. Sankey diagram of the scenario Smart Energy Denmark 2045 [14].

Table 1
Electricity demands in the Smart Energy Denmark 2045.

Demand type	Demand [TWh]
Classical demand (non-flexible electricity demand, such as appliances, lightning etc.) and industry	41.43
Electricity for heating and cooling	7.56
Electricity for transport and flexible demand	18.22
Electricity for electrolysis and e-fuels	26.80

Table 2
Costs and technical assumptions for renewable energy technologies used towards 2045.

	Offshore wind	Onshore wind	Photo voltaic
Investment cost (including grid connection) (M EUR/MW)	1.90	1.03	0.60
Fixed operation and maintenance (% of investment)	1.67	2.51	1.5
Technical lifetime (years)	30	30	40
Capacity factor	0.51	0.37	0.14

based on variable RES and biomass. The overall layout of this scenario is shown in Fig. 1. Hence, the study covers all energy demands relevant to a future energy transition. This includes electricity demands, both traditional demands and electrification of industry, transport, and heating. Furthermore, process industrial demands, heating demands, and transport demands, that cannot be covered in direct electrification are also included and assisted through Power-to-X, waste energy and combustion of fuels.

To summarize the electricity demands across sectors, Table 1 shows the resulting electricity demands.

While the demands are the same regardless of whether they are supplied by RES or nuclear power, the system designs are different. These differences are highlighted in the following two subsections, to detail how difference between RES and nuclear power impacts the system analysis.

2.2. Assumptions for renewable energy and nuclear power

The Smart Energy Denmark scenario cost and technology assumptions are documented in [3,14,67]. Furthermore, a report (in Danish) summarizes the important data [66].

Regarding cost data, all costs are represented as 2035 costs to represent investments over time from now towards 2045.

For RES, the capacity factors are based on the national estimations based on Danish weather patterns. Hence these are used to adjust time-series profiles of current wind and solar energy production data. For the case of Smart Energy Denmark, these are based on the Danish Energy Agency's technology catalogue, from which investment costs, operation, and maintenance costs as well as technical lifetime is found. Table 2 summarizes these numbers for offshore wind, onshore wind and photovoltaic.

Nuclear power station operators seek to maximize the capacity factor, as these plants are high investment technologies which potentially can operate at full capacity nearly all the time, provided the energy system allows for it and the plant is not experiencing technical issues. Thus, nuclear power in this study operates at a default capacity factor of 90% due to planned maintenance not allowing for full operation hours all the time. Due to energy system constraints, there might be reasons for

Table 3
Costs and technical assumptions for a various number of nuclear power stations used in the different parts of this paper. For the energy system analyses the 2035 and 2050 costs are used.

	Olkiluoto 3	Flamanville 3	Hinkley Point C	2050 IEA cost	2035 average cost
Investment cost (M EUR/MW)	6.88	7.94	8.98	4.5	6.18
Fixed operation and maintenance (EUR/MWh)	14.26	14.26	14.26	14.26	14.26
Fuel costs (EUR/MWh)	9.33	9.33	9.33	9.33	9.33
Technical lifetime (years)	60	60	60	60	60
Capacity factor	0.9	0.9	0.9	0.9	0.9
Load range	0.25–1	0.25–1	0.25–1	0.25–1	0.25–1

down regulating the nuclear power stations, thus as an output the capacity factor might be lower than 90%, but never higher. The study allows for nuclear power to be down regulated to 25% of the maximum load in for instance hours with high wind and solar production.

In the effort to achieve high capacity factors, the nuclear power stations operate in combination with the energy system. In the specific analyses, electrolysers are used to produce hydrogen in hours with low electricity demands. Electrolysis is chosen since hydrogen has a clear value in the hard-to-abate sectors such as heavy transport, aviation, and certain industrial demands. Other applications are possible too, such as steam production to industry. However, these are not included in here, partly because it may be difficult to distribute steam from the large conventional nuclear power stations assumed in this study, and partly because the industrial scenario in Smart Energy Denmark relies on a large degree of electrification and use of district heating.. With continued development, small modular reactor designs may provide new options for distributed nuclear-based steam generation. Also, by investigating the costs of Thermal Energy Storages highlighted in [47,49], Thermal Energy Storages are not included as the chosen flexibility measure in this study. However as shown in the forementioned studies, it can potentially have a role to play in future carbon neutral energy systems under the right circumstances.

In terms of costs, current investment costs of nuclear power in Europe are quite uncertain, with three European projects going vastly over budget. Furthermore, the IEA estimates an investment cost of 4500 USD/kW in 2050. Thus, to estimate investment costs in 2035, an average between the three European Pressurized Reactors (EPR) Hinkley Point C [68], Flamanville 3 [69] and Olkiluoto 3 [70] is used to represent current costs, while 4500 USD/kW [28] is used as a future cost. The 2035 costs used in the present analyses are therefore the average cost between these two points. In the analyses we have included the assumption that the technical lifetime of nuclear power plant is 60 years.

For operation and maintenance costs, as well as fuel costs, the costs estimated in the IEA LCOE (Levelized Cost of Energy) calculator are used [71,72]. Specifically, the costs for the EPR reactor are used. Table 3 summarizes the specific assumptions for nuclear power.

Furthermore, it should be noted that decommissioning costs are not included in the assessment – neither for nuclear nor for other technologies. Costs of externalities such as air pollution from extraction and resource consumption are also not included.

2.3. The energy system simulation tool EnergyPLAN

The analyses are carried out using EnergyPLAN [73] for the energy systems' simulations. This tool simulates energy systems with a temporal resolution of one hour for an entire year and ensures demand and supply for all relevant energy carriers balance in every time step. It is designed to model smart energy systems, and as such enables modelling of all energy demands including heating, cooling, electricity, transport, and industry. EnergyPLAN has a large technology portfolio that includes conventional energy technology such as boilers, power stations, combined heat and power plants and nuclear power; renewable energy technologies such as wind, hydro, solar heating, and PV as well as novel conversion technologies such as electrolysers, Power-to-X facilities, HTL (hydrothermal liquefaction) and Pyrolysis. To seek balance in all parts of the energy system on an hourly level, EnergyPLAN coordinates and integrates the operation of the supply side with the demand side through flexibility providers including storages across different energy grids (batteries, thermal storage, hydrogen storage e.g.), and sector coupling between different sectors.

By using a simulation tool, we are able to study and design specific options and solutions that an optimization model might miss, either because it does not consider all the needed system links or because it would be disregarded as being a sub-optimal solution.

EnergyPLAN has been used for many studies validating the model [74]. These models include country specific models such as energy scenarios for Chile [75], Hungary [76], Italy [77], Germany [78], China [79–81] and Denmark [14,15], as well as technology-specific analyses looking into e.g. storages [16], vehicle-to-grid [82], Carnot batteries [49], excess heat [83,84], and heat pumps [85].

EnergyPLAN has two primary simulation strategies: a technical and economic. In this article, the technical simulation strategy is applied to investigate nuclear power and renewables in a carbon neutral energy system. This means that based on an advanced merit order, which very simply described, gives priority to RES and nuclear power (only curtailing nuclear when excess production occurs), then comes heat pumps and combined heat and power plants (CHP) and finally, peak load power stations and boilers to supply electricity and heating demands. For more details see [73]. In that sense, the operational goal in this simulation strategy is to maximize the utilization of RES and/or nuclear, by implementing sector coupling and system integration technologies. This means that electrolysers, heat pumps, smart charging of electric vehicles (EVs) and other technologies all strive to primarily use electricity from RES and nuclear power. Other power producing units will only be activated in hours where the demand exceeds the production provided by RES and nuclear, first CHP plants and finally peak load power stations.

In the study, EnergyPLAN is used for calculating the total costs of each energy system scenario, described below. EnergyPLAN expresses these as Total Annual Costs. The total annual costs are broken into actual annual costs such as fuel costs, variable, and fixed operation and maintenance costs. For investments these are annualized over a defined period and discounted using an interest rate (this study uses an interest rate of 3%). All inputs can be defined by the user, but for the study presented in this paper, the technical lifetime of each technology is used as time period. Thus, the investment in e.g., nuclear power is annualized over a 60-year technical lifetime. By adding the annualized investment cost with the annual fuel costs, operation, and maintenance costs, etc., the total annual costs are achieved. In the economic comparisons in the study, we use the total annual costs for the entire energy system, to compare the different scenarios. This allows us to account for all system costs and benefits when evaluating the different technologies.

2.4. Designing scenarios in EnergyPLAN

To analyze the different setups between nuclear and renewable power the study takes the Smart Energy Denmark 2045 scenario as point of departure, reflecting three primary scenarios. The first scenario is the reference scenario with *Renewables Only*, the second scenario is a *1 GW Nuclear* scenario, and the third overall scenario is with a major shift from RES to nuclear – a *High Nuclear* scenario.

Smart Energy Denmark 2045 has two key targets. To provide cost-efficient carbon neutral energy systems, and to do this while meeting biomass availability constraints. These are key parameters in the further analysis of renewable energy and nuclear power. Thus, in the analyses carried out in this study, both the renewable and nuclear based energy systems have the following guiding principles:

1) Biomass consumption equal to 41.5 TWh, as to keep the biomass consumption within sustainable levels.
2) An export of biogas equal to 3.5 TWh, as it is expected that the biogas potential in Denmark is larger than in general in Europe.
3) Maximum curtailment of excess electricity of 5 TWh of electricity, as to make the scenarios comparable.
4) All scenarios must balance so energy demands are covered each hour of the year.

Besides zero carbon emissions, these are the key parameters to maintain, when changing the energy system designs between nuclear power and renewable energy.

The main change between the scenarios is that nuclear power will gradually replace offshore wind power. Thus, when nuclear power capacity increases, offshore wind power capacity decreases.

To ensure the maintenance of the performance parameters, the different scenarios are not only adjusted in electricity production capacity but also by varying electrolysers capacity (a combination of PEM, SOEC and alkaline electrolysis), hydrogen storage and CHP/power stations, alongside the capability of nuclear load reduction in hours with too much excess electricity. This allows for a comparison with equal performance between the scenarios.

In here, the need for electrolysis capacity and hydrogen storage is investigated, as it provides the highest marginal flexibility cost in the system. For RES, electrolysers are used to ensure large amounts of electricity being converted to hydrogen and being stored from one hour to another, with the objective of producing electrofuels for the transport sector. These electrofuels ensure lower biomass needs as well as reduces the biogas export. For nuclear power, the electrolysers ensure a high capacity factor, as nuclear power has a relative flat production profile. Thus, high nuclear capacity factors are ensured by ramping up hydrogen production in hours with low electricity demand and lowering hydrogen production in hours with high demand. Thus, allowing for a stable output of electricity from the nuclear power station. This operating pattern should require lower electrolyser capacity and lower hydrogen storage sizes than is the case in a renewable energy system. Thus, the analyses in this paper answer, whether these lower investments into flexibility measures can outweigh the high investments in the nuclear power technology.

Nuclear power has the potential to provide excess heat for the district heating grids in Denmark, thus, both nuclear scenarios have two sub-scenarios either including or excluding DH utilization. To model the district heating production from nuclear power plants, electric and thermal capacity will be adjusted from the original electric capacity. Hence during the heating season (October 1st to April 30th), electric capacity will be lowered as the plant will also generate district heating. Outside the heating season, the plant maintains original electric production capacity, equal to the scenarios without district heating capabilities. As district heating supply is based on geographical location in the vicinity of a district heating grid, the study utilizes information from Heat Plan Denmark 2021 and IDA's Climate Response to assess the potential for heat delivery. Based on technology data for the switching in operation between condensing mode and back-pressure mode for an extraction mode coal-fired CHP unit [86], the different capacities for heat and electricity production are estimated. This information has to be combined with the estimated heat outputs. For the 1 GW Nuclear scenario the potential utilizable heat output is 5.77 TWh. Hence 1 GW electric capacity in condensing mode equals 850 MW electric capacity and 1250 MW heat capacity in back pressure. The High Nuclear scenario can include 10.50 TWh heat from nuclear power in the district heating grids, which is the maximum capacity for baseload district heating supply after utilization of excess heat from industry. Hence this this results in 7.68 GW electricity capacity in condensing mode converts to 7.52 GW electric capacity and only 2.28 GW thermal capacity as the district heating systems cannot take more baseload heat. To create space in the district heating system, heat pump capacity and heat delivered from geothermal heat are reduced.

Table 4
Electricity capacity in all scenarios.

	Only Renewables	1 GW Nuclear		High Nuclear	
	Smart Energy Denmark	Without DH utilization	With DH utilization	Without DH utilization	With DH utilization
Onshore wind	5.0 GW	5.0 GW	5.0 GW	4.7 GW	4.7 GW
Offshore wind	14.1 GW	12.6 GW	12.7 GW	2.3 GW	2.3 GW
Photo voltaic	10.0 GW	10.0 GW	10.0 GW	2.0 GW	2.0 GW
Nuclear power	0.0 GW	1.0 GW	1.0 GW	7.4 GW	7.5 GW

Hence, the results from the analyses focus on the differences in total annual costs as well as changes in the primary energy supply. These two results form the basis for considering how nuclear potentially impacts the energy transition compared RES.

All the scenarios are calculated with an interest rate of 3%. All costs related to the Smart Energy Denmark scenario are documented here [14,66] with costs related to nuclear power and changes in the system being documented in Section 2.2.

The specific model setups are described in Section 3, which also highlights the results from the scenario design specifying the production and flexibility capacities to ensure an equal comparison.

3. Scenario design and specifications

All inputs are based on the IDA's Climate Response [66] and the Smart Energy Denmark [14] scenario for 2045. All inputs and outputs for the renewable-only scenario are thus based on this scenario. The data for these as well as all models presented in the study are downloadable from [87].

These analyses compare the *Renewables Only* scenario to two alternative scenarios with nuclear power as part of the future Danish energy system. The first alternative is a scenario with a *1 GW Nuclear* power station in a future decarbonized energy system. The second is a *High Nuclear* scenario, with only the current Danish renewable capacity being kept and any further development only in nuclear.

In the 1 GW Nuclear scenario, RES, either onshore or offshore wind power, is reduced so the total amount of produced CO_2 neutral electricity is the same. The same step is done in the High Nuclear scenario. Table 4 show the difference in electricity capacity between the systems.

In the two nuclear scenarios, nuclear power can provide heating through district heating. These two sub scenarios impact the electricity capacity in the heating season to ensure a heat output. For the *1 GW Nuclear* scenario, the electric capacity is reduced from 1000 MW to 850 to provide 1250 MW heat. For the *High Nuclear* scenario, the electricity capacity is reduced from 7581 MW to 7380 MW to provide 2280 MW heat. To allow for this level of heat into the system, heat pump capacity in the central district heating areas is lowered from 1600 to 1100 MW, and there is no room for geothermal heat compared to the renewable scenario. By leaving out geothermal energy, it allows for the maximum utilization of heat from the nuclear power stations and the change in heat pumps ensures balancing with the main balancing parameters introduced in Section 2.3.

To adjust flexibility measures between the systems, each scenario has

Table 5
Flexibility capacity in all scenarios.

	Only Renewables	1 GW Nuclear		High Nuclear	
	Smart Energy Denmark	Without DH utilization	With DH utilization	Without DH utilization	With DH utilization
Central CHP capacity	3.1 GW	3.1 GW	3.1 GW	3.1 GW	1.7 GW
Peak load power plant capacity	1.7 GW	1.7 GW	1.7 GW	1.7 GW	1.7 GW
Electrolysis capacity	4.8 GW	4.3 GW	4.3 GW	3.3 GW	3.3 GW
Hydrogen storage	320 GWh	320 GWh	320 GWh	0 GWh	0 GWh

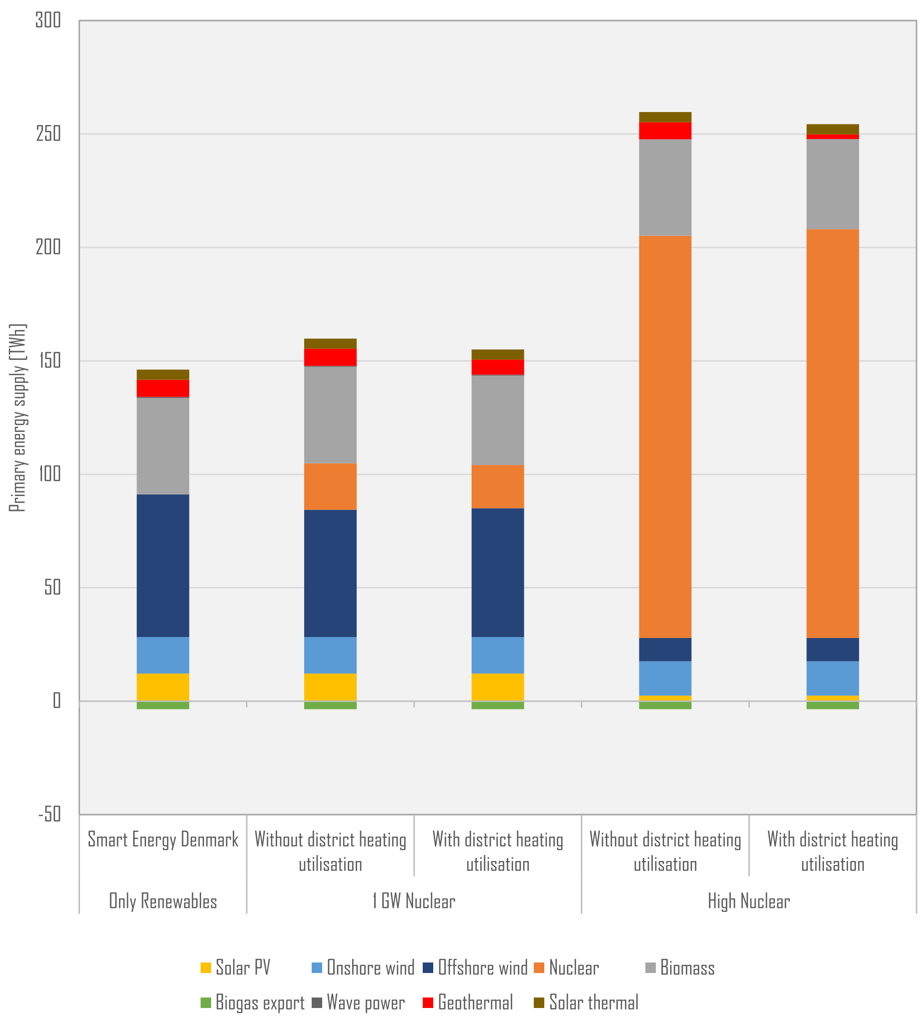

Fig. 2. Primary energy consumption across all the energy scenarios. Nuclear power is represented with the thermal energy produced based on a turbine efficiency of 33% electric.

different electrolyser and hydrogen storage capacities as well as capacities on CHP and power stations. These are highlighted in Table 5.

4. Results

The results in this section highlight how the energy system composition changes between the three scenarios, by focusing on primary energy consumption, changes in flexibility and the differences in costs.

4.1. Primary energy consumption in the scenarios

Fig. 2 shows the primary energy consumption across the systems. From here it is seen that in the 1 GW Nuclear scenario there are very small effects compared to the Only Renewables scenario – the system it is still dominated by offshore wind power as the main energy supplier. However, in the High Nuclear scenario, the share of renewable electricity production is reduced significantly and replaced by a high share of nuclear power in the system. The remaining primary energy sources are constant across all scenarios – the reason is that for some cases they are providing energy for hard-to-abate sectors such as industry and transport, and else, for instance biogas, provides flexibility both in the Renewable Only scenario and the high nuclear scenario. The primary energy consumption increases quite significantly since the thermal efficiency of the nuclear power station is 33% [88].

4.2. Flexibility requirements in the scenarios

The difference in flexibility is highlighted in Figs. 3 and 4, which show hour by hour electricity production for the entire modelled year in the Only Renewables scenario (Fig. 3) and the High Nuclear scenario

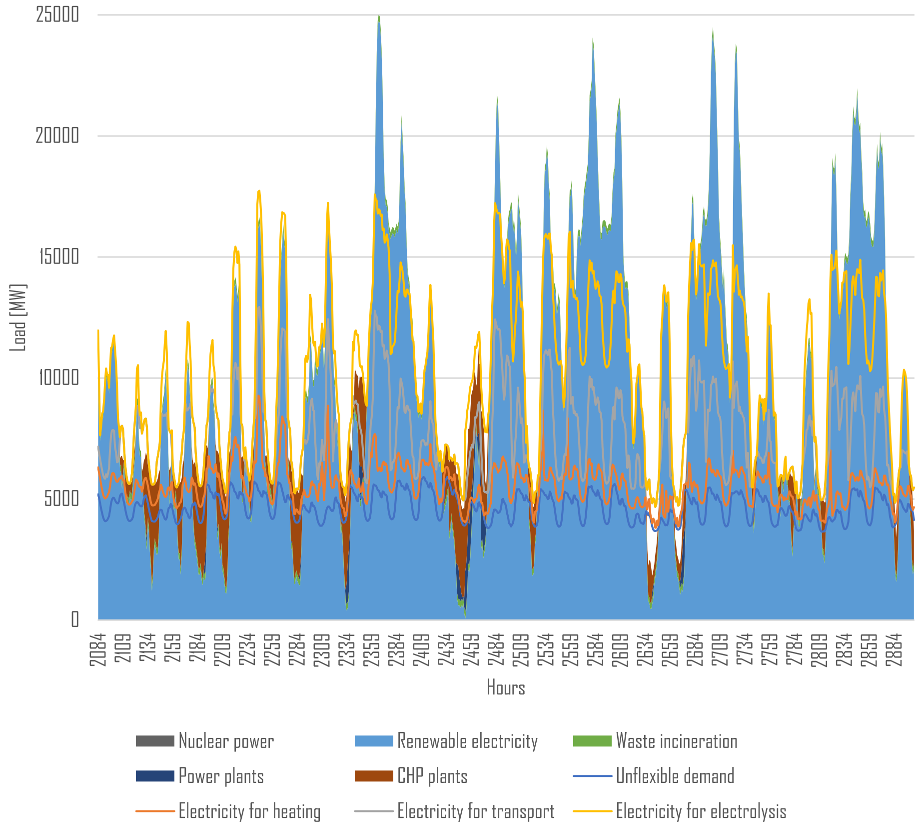

Fig. 3. Electricity production and demands in April 2045 in the Only Renewable scenario corresponding to a 2045 100% renewable energy system for Denmark. A figure for the entire year is found in Supplementary Material. Both the area and lines are stacked. In hours where the supply (areas) exceeds the demand (lines), energy is exchanged to surrounding areas or curtailed. In hours where the demand exceeds the area, electricity is imported.

with district heating (Fig. 4). When comparing the two figures, it is clear how the different energy systems behave. In both energy systems, the classical demand is non-flexible, and, thus, must be provided in the right quantity at the specific time. Electricity for heating, electricity for transport and electricity for electrolysers provide the flexibility in the systems, using energy storages.

In the Only Renewables scenario, renewable energy can cover almost all the classical electricity demand without flexibility. It is also shown in Fig. 3 that the flexibility kicks in to utilize or store excess as heat or hydrogen in hours with abundant wind and solar production. The storages then assist the system by delivering the heat and hydrogen needed in hours with less wind and solar production. In the remaining gaps, in hours with low wind and solar resources, combined heat and power stations and peak load power plants running on biogas covers the load in combination with electricity exchange. This setup requires both a large capacity of RES as well as substantial flexibility capacities and storages to help maneuver the excess electricity to the right hours.

In the nuclear based scenarios, the flexibility is instead used to maintain a constant production on the nuclear power station. Thus, the flexibility capacity, e.g., in the electrolysers and the required storage capacity, is primarily needed to cycle through diurnal variations in demands as well as some seasonal and weekday/weekend peaks/lows. Hence, in the High Nuclear Scenario it is possible to achieve a constant operation of the nuclear power station, and instead of regulating nuclear power up and down, the hydrogen is produced flexibly and used for hard-to-abate sectors such as transport and industry. In general, this means a lower flexibility requirement in the nuclear alternatives than in the Only Renewable scenario. However, the question becomes if this lower flexibility requirement can offset costs of nuclear power.

4.3. System costs of the scenarios

The total annual costs compared between all the investigated scenarios are shown in Fig. S1 in the supplementary material. Fig. 5 highlights the differences between the scenarios, indicating the costs that are different. The reason for this depiction is that the primary cost part of all the investigated scenarios is not related to electricity production. These are instead investments in the transport sector, sector coupling, district heating, industrial transition, and energy savings to mention the main costs Excluded from the figure. When going from the Only Renewables scenario to the High Nuclear scenario, the annualized investment costs increase slightly. Furthermore, the operation and maintenance costs as well as the fuel costs increase, due to higher annual costs associated with in the nuclear scenarios. The total system changes therefore indicate that the nuclear power scenarios are more expensive than renewable only. The increase in costs is both due to higher investment costs in nuclear power as well as operation. The other infrastructural costs do, however, result in some savings, compared to the Only Renewables scenario.

With Fig. 5 showing that the nuclear power scenarios are more expensive than the Only Renewables scenarios, Fig. 6 shows the difference in costs in two main nuclear scenarios. For each scenario, the blue column shows changes in total annual costs, not including changes in the flexibility measures – meaning power plant operation and investments in electrolysis and hydrogen storage. For all scenarios, it is seen that the savings in power plant operation and flexibility cannot cover the excess costs of nuclear power. It is also seen that to achieve the lowest nuclear scenario costs, district heating utilization is an advantage, but again does not offer a sufficiently large advantage to match the costs of the Only Renewables scenario.

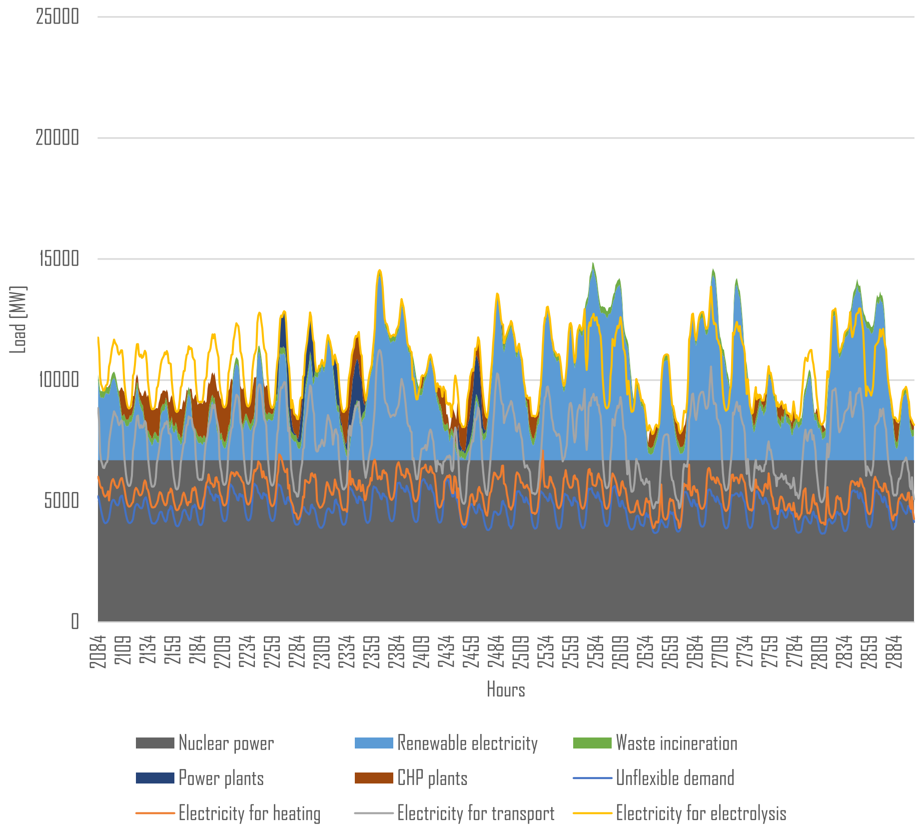

Fig. 4. Electricity production and demands in April in 2045 in the High Nuclear scenario for Denmark. A figure for the entire year is found in Supplementary Material. Both the area and lines are stacked. In hours where the supply (areas) exceeds the demand (lines), energy is exchanged to surrounding areas or curtailed. In hours where the demand exceeds the area, electricity is imported.

4.4. Sensitivity analysis

The final step in the analysis is to investigate how different capacity costs (CAPEX) of nuclear power would impact the highlighted results shown in Fig. 6. Fig. 7 therefore shows the High Nuclear scenario with district heating utilization at three different price reductions, compared to the base price of 6.18 MEUR/MW (cf. Table 3). The study tests for 75%, 50% and 25% reductions of this investment cost, to show how low nuclear costs must be, to be competitive against the Only Renewables scenario. Fig. 7 show the capacity cost of nuclear power must be as low as 25% of the price estimate used in the main analyses. Thus, nuclear power would have to reach a capacity cost of 1.55 MEUR/MW, for it to be competitive with renewable energy as implemented in the Only Renewables scenario. This is an extremely optimistic price and the IEA World Energy Outlook, for comparison, expresses a European nuclear price in 2050 to be 4.5 MUSD/MW (4.14 MEUR/MW at today's rate), almost three times higher than this highly optimistic price.

5. Conclusion

Based on the presented smart energy systems analysis of renewable energy and nuclear power during the green transition, it is shown that both technologies can provide electricity for a carbon free energy system, and that it is possible to balance energy systems that are 100% renewable but also predominantly based on nuclear power without relying on fossil fuels or large investments in electricity storage.

The flexibility requirements are, however, somewhat different between the two systems. For the renewable based energy system, the flexibility measures must be able to handle very high loads in certain hours and vice versa offset very low loads in other hours. To do this, sufficient RES must be installed to enable these in most of the time to cover the entire classical non-flexible demand. Furthermore, heat pumps, electrolysers, smart charge of EVs, and storages must be able to handle production exceeding the classical demand.

For the nuclear power-based system, the flexibility measures must instead deal with a technology that strives towards constant production. Therefore, the nuclear power capacity is aimed at a level, where constant production is achieved, and the flexibility mostly lies in shifts between day and night operation. Thus, especially the electrolysis capacity can be lowered compared to a renewable energy-based system. In total, the electrolysis capacity drops from 4800 MW in the Only Renewables scenario to 3300 MW in the High Nuclear scenario. Furthermore, the required hydrogen storage capacity is lowered from 320 GWh to 0 GWh.

Thus, the flexibility costs are lower in the scenarios with nuclear power, but the high investment costs in nuclear power alongside cost for fuel and operation and maintenance more than tip the scale in favor of the Only Renewables scenario. The costs of investing in and operating the nuclear power plants are simply too high compared to Only Renewables scenario, even though more investment must be put into flexibility measures in the latter. In the Danish case, to achieve a more cost-efficient system based predominantly on nuclear power – the investment costs would have to drop to 1.55 MEUR/MW. This is significantly below any current or future cost projection for nuclear power.. Such a high cost-margin indicates that a combination of low-cost RES and sector coupling presents a cost-effective energy transition making it very hard for nuclear power to deliver a competitive alternative. It is important to mention that RES are geographically and weather-dependent with, e.g., Denmark having advantageous wind resources that can be leveraged. Thus, the energy system and available alternative renewable energy resources will impact the feasibility of nuclear power. Regardless, the study clearly shows the need to include sector coupling

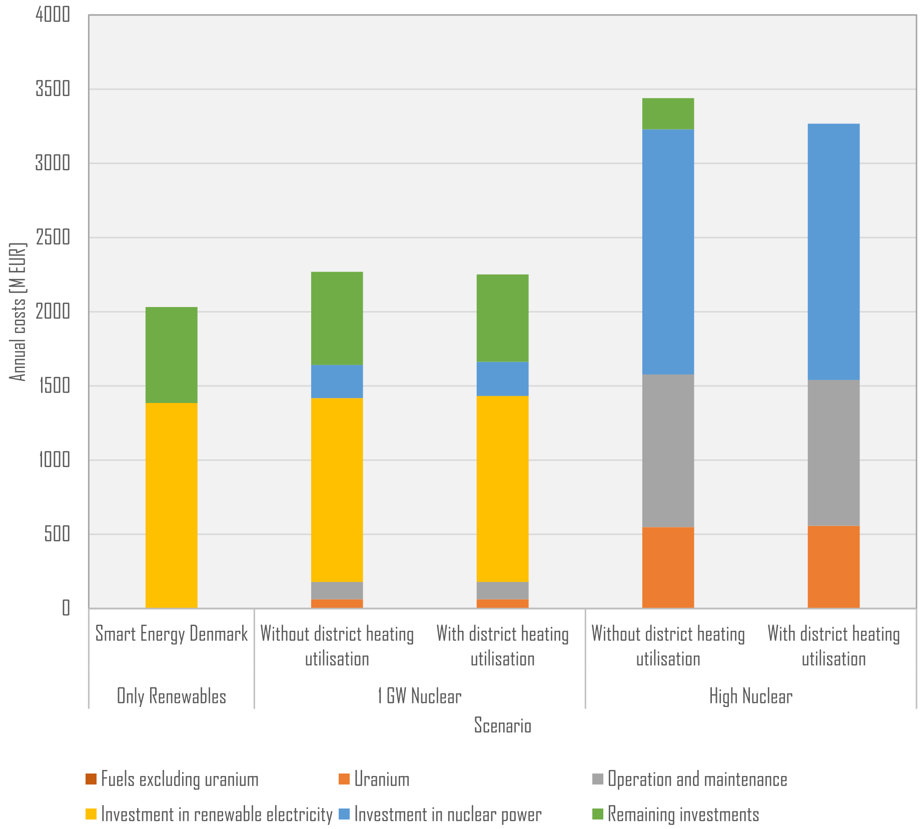

Fig. 5. Differences in total annual costs between the energy scenarios investigated in this study. Remaining investments cover extra flexibility and heat supply costs not needed in the high nuclear scenario. This figure excludes fixed costs that are common in all scenarios.

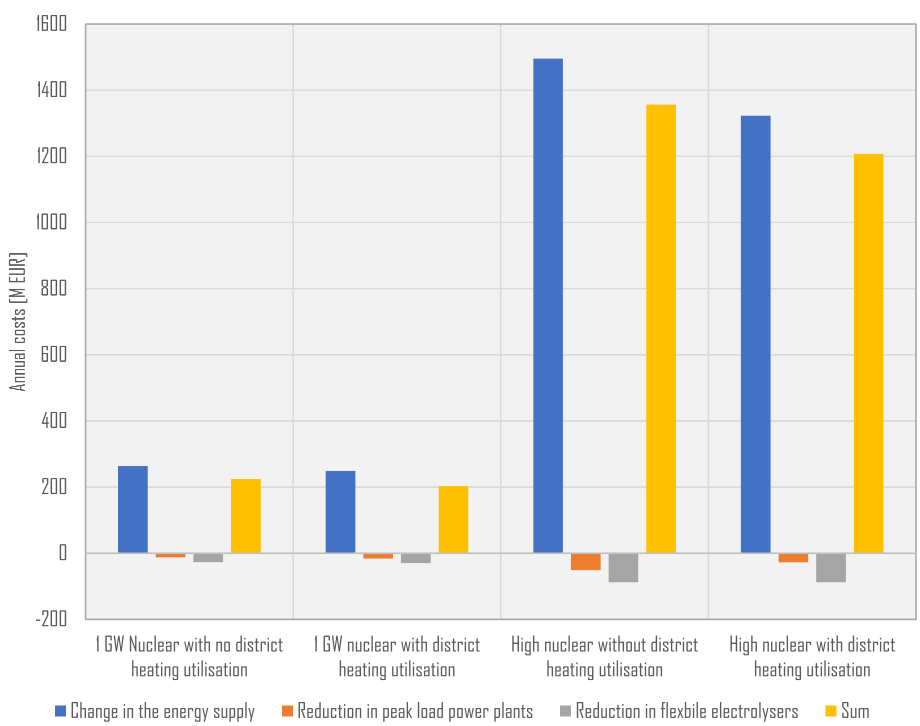

Fig. 6. Additional annualized costs in the 1 GW Nuclear scenario and the High Nuclear scenario compared to the Only Renewables scenario. Both nuclear scenarios are shown with and without district heating utilization.

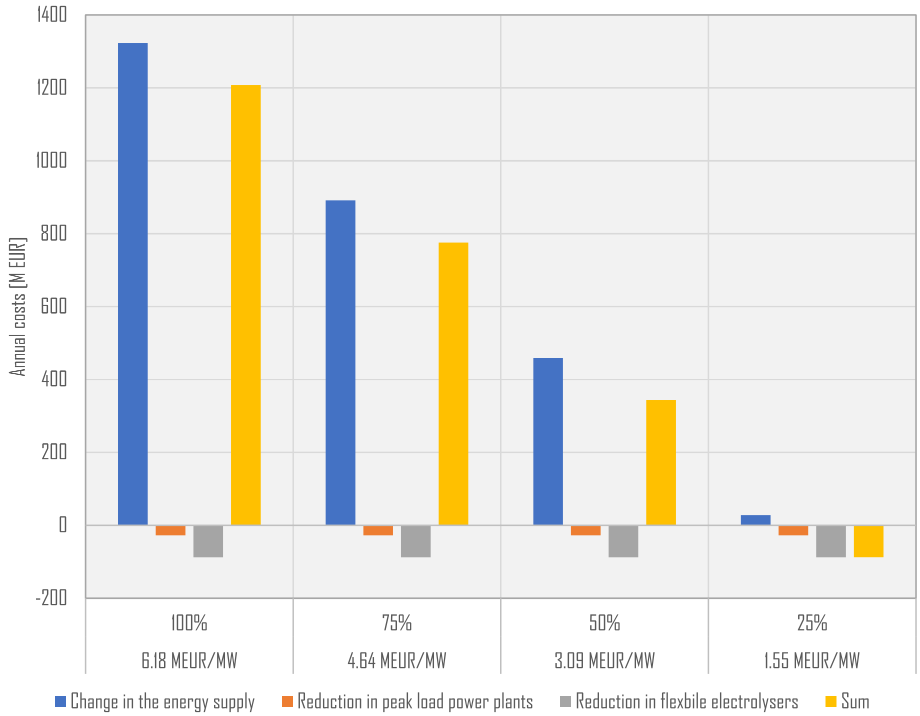

Fig. 7. Sensitivity analysis of different costs for nuclear power with impacts on total annual costs. Results shown for the High Nuclear scenario with district heating utilization compared to the Only Renewables scenario.

and the entire energy system when conducting energy system analyses and comparing alternatives.

CRediT authorship contribution statement

Jakob Zinck Thellufsen: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Henrik Lund:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Brian Vad Mathiesen:** Writing – review & editing, Conceptualization. **Poul Alberg Østergaard:** Writing – review & editing, Methodology, Conceptualization. **Peter Sorknæs:** Writing – review & editing, Validation, Methodology. **Steffen Nielsen:** Writing – review & editing. **Poul Thøis Madsen:** Writing – review & editing. **Gorm Bruun Andresen:** Writing – review & editing, Conceptualization.

Declaration of competing interest

None.

Data availability

The data and models are available from the website https://www.energyplan.eu/atomkraft

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2024.123705.

References

[1] Thellufsen JZ, Lund H, Sorknæs P, Nielsen S, Chang M, Mathiesen BV. Beyond sector coupling: utilizing energy grids in sector coupling to improve the European energy transition. Smart Energy 2023;12:100116. https://doi.org/10.1016/J.SEGY.2023.100116.
[2] Korberg AD, Brynolf S, Grahn M, Skov IR. Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. Renew Sustain Energy Rev 2021;142:110861. https://doi.org/10.1016/J.RSER.2021.110861.
[3] Kany MS, Mathiesen BV, Skov IR, Korberg AD, Thellufsen JZ, Lund H, et al. Energy efficient decarbonisation strategy for the Danish transport sector by 2045. Smart Energy 2022;5:100063. https://doi.org/10.1016/J.SEGY.2022.100063.
[4] Sorknæs P, Johannsen RM, Korberg AD, Nielsen TB, Petersen UR, Mathiesen BV. Electrification of the industrial sector in 100% renewable energy scenarios. Energy 2022;254:124339. https://doi.org/10.1016/J.ENERGY.2022.124339.
[5] Mathiesen BV, Johannsen RM, Kermeli K, Crijns-Graus W, Lund H, Skov IR. The green transition of industry – an introduction to IndustryPLAN. Smart. Energy 2023:11. https://doi.org/10.1016/j.segy.2023.100111.
[6] Paardekooper S, Lund H, Zinck J, Nis T, Brian B, Mathiesen V. Heat roadmap Europe: strategic heating transition typology as a basis for policy recommendations. Energ Effic 2003;15:32. https://doi.org/10.1007/s12053-022-10030-3.
[7] Thomaßen G, Kavvadias K, Jiménez Navarro JP. The decarbonisation of the EU heating sector through electrification: a parametric analysis. Energy Policy 2021;148:111929. https://doi.org/10.1016/J.ENPOL.2020.111929.
[8] Korberg AD, Thellufsen JZ, Skov IR, Chang M, Paardekooper S, Lund H, et al. On the feasibility of direct hydrogen utilisation in a fossil-free Europe. Int J Hydrogen Energy 2022. https://doi.org/10.1016/J.IJHYDENE.2022.10.170.
[9] Korberg AD, Skov IR, Mathiesen BV. The role of biogas and biogas-derived fuels in a 100% renewable energy system in Denmark. Energy 2020;199:117426. https://doi.org/10.1016/J.ENERGY.2020.117426.
[10] Sorknæs P, Nielsen S, Lund H, Mathiesen BV, Moreno D, Thellufsen JZ. The benefits of 4th generation district heating and energy efficient datacentres. Energy 2022;260:125215. https://doi.org/10.1016/J.ENERGY.2022.125215.
[11] Sorknæs P, Østergaard PA, Thellufsen JZ, Lund H, Nielsen S, Djørup S, et al. The benefits of 4th generation district heating in a 100% renewable energy system. Energy 2020:213. https://doi.org/10.1016/j.energy.2020.119030.
[12] Lund H, Andersen AN, Østergaard PA, Mathiesen BV, Connolly D. From electricity smart grids to smart energy systems - a market operation based approach and understanding. Energy 2012;42:96–102. https://doi.org/10.1016/j.energy.2012.04.003.
[13] Mathiesen BV, Lund H, Connolly D, Wenzel H, Ostergaard PA, Möller B, et al. Smart energy systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54. https://doi.org/10.1016/J.APENERGY.2015.01.075.
[14] Lund H, Thellufsen JZ, Sorknæs P, Mathiesen BV, Chang M, Madsen PT, et al. Smart energy Denmark. A consistent and detailed strategy for a fully decarbonized society. Renew Sustain Energy Rev 2022;168:112777. https://doi.org/10.1016/J.RSER.2022.112777.
[15] Thellufsen JZ, Lund H, Sorknæs P, Østergaard PA, Chang M, Drysdale D, et al. Smart energy cities in a 100% renewable energy context. Renew Sustain Energy Rev 2020. https://doi.org/10.1016/j.rser.2020.109922.
[16] Lund H, Østergaard PA, Connolly D, Ridjan I, Mathiesen BV, Hvelplund F, et al. Energy storage and smart energy systems. Int J Sustain Energy Plan Manag 2016;11:3–14. https://doi.org/10.5278/ijsepm.2016.11.2.
[17] Brown T, Schlachtberger D, Kies A, Schramm S, Greiner M. Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable

European energy system. Energy 2018;160:720–39. https://doi.org/10.1016/J.ENERGY.2018.06.222.
[18] Pedersen TT, Victoria M, Rasmussen MG, Andresen GB. Modeling all alternative solutions for highly renewable energy systems. Energy 2021;234:121294. https://doi.org/10.1016/J.ENERGY.2021.121294.
[19] Tröndle T, Lilliestam J, Marelli S, Pfenninger S. Trade-offs between geographic scale, cost, and infrastructure requirements for fully renewable electricity in Europe. Joule 2020;4:1929–48. https://doi.org/10.1016/J.JOULE.2020.07.018.
[20] Kountouris I, Bramstoft R, Madsen T, Gea-Bermúdez J, Münster M, Keles D. A unified European hydrogen infrastructure planning to support the rapid scale-up of hydrogen production A unified European hydrogen infrastructure planning to support the rapid scale-up of hydrogen production. 2023. https://doi.org/10.21203/rs.3.rs-3185467/v1.
[21] Pavičević M, Mangipinto A, Nijs W, Lombardi F, Kavvadias K, Jiménez Navarro JP, et al. The potential of sector coupling in future European energy systems: soft linking between the Dispa-SET and JRC-EU-TIMES models. Appl Energy 2020;267:115100. https://doi.org/10.1016/J.APENERGY.2020.115100.
[22] Thellufsen JZ, Lund H. Cross-border versus cross-sector interconnectivity in renewable energy systems. Energy 2017:124. https://doi.org/10.1016/j.energy.2017.02.112.
[23] Gea-Bermúdez J, Jensen IG, Münster M, Koivisto M, Kirkerud JG, Chen Y, et al. The role of sector coupling in the green transition: a least-cost energy system development in northern-Central Europe towards 2050. Appl Energy 2021;289:116685. https://doi.org/10.1016/J.APENERGY.2021.116685.
[24] Saidi K, Omri A. Reducing CO2 emissions in OECD countries: do renewable and nuclear energy matter? Progress Nuclear Energy 2020;126:103425. https://doi.org/10.1016/J.PNUCENE.2020.103425.
[25] Ahmad A, Covatariu A, Ramana MV. A stormy future? Financial impact of climate change-related disruptions on nuclear power plant owners. Util Policy 2023;81:101484. https://doi.org/10.1016/J.JUP.2022.101484.
[26] Eash-Gates P, Klemun MM, Kavlak G, McNerney J, Buongiorno J, Trancik JE. Sources of cost overrun in nuclear power plant construction call for a new approach to engineering design. Joule 2020;4:2348–73. https://doi.org/10.1016/J.JOULE.2020.10.001.
[27] Sovacool BK, Gilbert A, Nugent D. An international comparative assessment of construction cost overruns for electricity infrastructure. Energy Res Soc Sci 2014;3:152–60. https://doi.org/10.1016/J.ERSS.2014.07.016.
[28] IEA. World energy outlook 2022. Paris. 2022.
[29] Steigerwald B, Weibezahn J, Slowik M, von Hirschhausen C. Uncertainties in estimating production costs of future nuclear technologies: a model-based analysis of small modular reactors. Energy 2023:281. https://doi.org/10.1016/j.energy.2023.128204.
[30] International Energy Agency. Nuclear Power and Secure Energy Transitions From Today's Challenges to Tomorrow's Clean Energy Systems. 2022.
[31] Dyck E. Exploring synergies between nuclear and renewables: IAEA meeting discusses options for decarbonizing energy production and cogeneration. Int Atomic Energy Agency 2018. https://www.iaea.org/newscenter/news/exploring-synergies-between-nuclear-and-renewables-iaea-meeting-discusses-options-for-decarbonizing-energy-production-and-cogeneration [accessed January 10, 2024].
[32] International Energy Agency. World Energy Model: Techno-economic Inputs. https://www.iea.org/reports/world-energy-model/techno-economic-inputs; 2021 (accessed October 17, 2022).
[33] Arefin MA, Islam MT, Rashid F, Mostakim K, Masuk NI, Islam MHI. A comprehensive review of nuclear-renewable hybrid energy systems: status, operation, configuration, benefit, and feasibility. Front Sustain Cities 2021:3. https://doi.org/10.3389/frsc.2021.723910.
[34] El-Emam RS, Constantin A, Bhattacharyya R, Ishaq H, Ricotti ME. Nuclear and renewables in multipurpose integrated energy systems: a critical review. Renew Sustain Energy Rev 2024;192:114157. https://doi.org/10.1016/J.RSER.2023.114157.
[35] Kan X, Hedenus F, Reichenberg L. The cost of a future low-carbon electricity system without nuclear power – the case of Sweden. Energy 2020;195:117015. https://doi.org/10.1016/J.ENERGY.2020.117015.
[36] Pattupara R, Kannan R. Alternative low-carbon electricity pathways in Switzerland and it's neighbouring countries under a nuclear phase-out scenario. Appl Energy 2016;172:152–68. https://doi.org/10.1016/J.APENERGY.2016.03.084.
[37] Olkkonen V, Ekström J, Hast A, Syri S. Utilising demand response in the future Finnish energy system with increased shares of baseload nuclear power and variable renewable energy. Energy 2018:164. https://doi.org/10.1016/j.energy.2018.08.210.
[38] Seck GS, Krakowski V, Assoumou E, Maïzi N, Mazauric V. Embedding power system's reliability within a long-term energy system optimization model: linking high renewable energy integration and future grid stability for France by 2050. Appl Energy 2020:257. https://doi.org/10.1016/j.apenergy.2019.114037.
[39] Hong JH, Kim J, Son W, Shin H, Kim N, Lee WK, et al. Long-term energy strategy scenarios for South Korea: transition to a sustainable energy system. Energy Policy 2019:127. https://doi.org/10.1016/j.enpol.2018.11.055.
[40] Pfenninger S, Keirstead J. Renewables, nuclear, or fossil fuels? Scenarios for Great Britain's power system considering costs, emissions and energy security. Appl Energy 2015;152:83–93. https://doi.org/10.1016/J.APENERGY.2015.04.102.
[41] Brouwer AS, van den Broek M, Seebregts A, Faaij A. Operational flexibility and economics of power plants in future low-carbon power systems. Appl Energy 2015:156. https://doi.org/10.1016/j.apenergy.2015.06.065.
[42] Fattahi A, Sijm J, Van den Broek M, Gordón RM, Dieguez MS, Faaij A. Analyzing the techno-economic role of nuclear power in the Dutch net-zero energy system transition. Adv Appl Energy 2022;7:100103. https://doi.org/10.1016/J.ADAPEN.2022.100103.
[43] Ruiz P, Nijs W, Tarvydas D, Sgobbi A, Zucker A, Pilli R, et al. ENSPRESO - an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials. Energ Strat Rev 2019:26. https://doi.org/10.1016/j.esr.2019.100379.
[44] Cárdenas B, Ibanez R, Rouse J, Swinfen-Styles L, Garvey S. The effect of a nuclear baseload in a zero-carbon electricity system: an analysis for the UK. Renew Energy 2023;205:256–72. https://doi.org/10.1016/J.RENENE.2023.01.028.
[45] Duan L, Petroski R, Wood L, Caldeira K. Stylized least-cost analysis of flexible nuclear power in deeply decarbonized electricity systems considering wind and solar resources worldwide. Nat Energy 2022;7:260–9. https://doi.org/10.1038/s41560-022-00979-x.
[46] Bryan J, Meek A, Dana S, Islam Sakir MS, Wang H. Modeling and design optimization of carbon-free hybrid energy systems with thermal and hydrogen storage. Int J Hydrogen Energy 2023:48. https://doi.org/10.1016/j.ijhydene.2023.03.135.
[47] Romanos P, Al Kindi AA, Pantaleo AM, Markides CN. Flexible nuclear plants with thermal energy storage and secondary power cycles: virtual power plant integration in a UK energy system case study. E-Prime Adv Electric Eng Electron Energy 2022;2:100027. https://doi.org/10.1016/J.PRIME.2021.100027.
[48] Nitsch F, Wetzel M, Gils HC, Nienhaus K. The future role of Carnot batteries in Central Europe: combining energy system and market perspective. J Energy Storage 2024;85:110959. https://doi.org/10.1016/J.EST.2024.110959.
[49] Sorknæs P, Thellufsen JZ, Knobloch K, Engelbrecht K, Yuan M. Economic potentials of Carnot batteries in 100% renewable energy systems. Energy 2023;282:128837. https://doi.org/10.1016/J.ENERGY.2023.128837.
[50] Al Kindi AA, Aunedi M, Pantaleo AM, Strbac G, Markides CN. Thermo-economic assessment of flexible nuclear power plants in future low-carbon electricity systems: role of thermal energy storage. Energ Conver Manage 2022;258:115484. https://doi.org/10.1016/J.ENCONMAN.2022.115484.
[51] Aunedi M, Al Kindi AA, Pantaleo AM, Markides CN, Strbac G. System-driven design of flexible nuclear power plant configurations with thermal energy storage. Energ Conver Manage 2023;291:117257. https://doi.org/10.1016/J.ENCONMAN.2023.117257.
[52] Masotti GC, Cammi A, Lorenzi S, Ricotti ME. Modeling and simulation of nuclear hybrid energy systems architectures. Energ Conver Manage 2023;298:117684. https://doi.org/10.1016/J.ENCONMAN.2023.117684.
[53] Gerkšič S, Vrančić D, Čalič D, Žerovnik G, Trkov A, Kromar M, et al. A perspective of using nuclear power as a dispatchable power source for covering the daily fluctuations of solar power. Energy 2023:284. https://doi.org/10.1016/j.energy.2023.128531.
[54] Qu C, Bang RN. Ride the wind or go nuclear? A private investment analysis. Energ Strat Rev 2023;50:101249. https://doi.org/10.1016/J.ESR.2023.101249.
[55] Bouramdane AA. Crafting an optimal portfolio for sustainable hydrogen production choices in Morocco. Fuel 2024;358:130292. https://doi.org/10.1016/J.FUEL.2023.130292.
[56] Kalinichenko D, Wodrich L, Lee AJH, Kozlowski T, Brooks CS. Analysis of nuclear microreactor efficacy with hydrogen production methods. Progress Nuclear Energy 2024;168:104994. https://doi.org/10.1016/J.PNUCENE.2023.104994.
[57] Ozcan H, Fazel H. Cost assessment of selected nuclear driven hybrid thermochemical cycles for hydrogen production. Int J Hydrogen Energy 2024;54:554–61. https://doi.org/10.1016/J.IJHYDENE.2023.07.127.
[58] Chalkiadakis N, Stamatakis E, Varvayanni M, Stubos A, Tzamalis G, Tsoutsos T. A new path towards sustainable energy transition: techno-economic feasibility of a complete hybrid small modular reactor/hydrogen (SMR/H2). Energy Syst Energies (Basel) 2023;16. https://doi.org/10.3390/en16176257.
[59] Constantin A. Nuclear hydrogen projects to support clean energy transition: updates on international initiatives and IAEA activities. Int J Hydrogen Energy 2024;54:768–79. https://doi.org/10.1016/J.IJHYDENE.2023.09.250.
[60] Mignacca B, Locatelli G. Economics and finance of small modular reactors: a systematic review and research agenda. Renew Sustain Energy Rev 2020;118:109519. https://doi.org/10.1016/J.RSER.2019.109519.
[61] Stewart WR, Shirvan K. Capital cost estimation for advanced nuclear power plants. Renew Sustain Energy Rev 2022;155:111880. https://doi.org/10.1016/J.RSER.2021.111880.
[62] Lazard. LCOE+. 2023.
[63] Connolly D, Lund H, Mathiesen BV. Smart energy Europe: the technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renew Sustain Energy Rev 2016;60:1634–53. https://doi.org/10.1016/j.rser.2016.02.025.
[64] Paardekooper S, Lund H, Thellufsen JZ, Bertelsen N, Mathiesen BV. Heat roadmap Europe: strategic heating transition typology as a basis for policy recommendations. Energ Effic 2022:15. https://doi.org/10.1007/s12053-022-10030-3.
[65] Ebergifakta Norge. Electricity production. Https://EnergifaktanorgeNo/En/Norsk-Energiforsyning/Kraftproduksjon/; 2024.
[66] Lund H, Mathiesen BV, Thellufsen JZ, Sorknæs P, Chang M, Kany MS, et al. IDAs Klimasvar 2045 – Sådan bliver vi klimaneutrale. 2021.
[67] Lund H, Skov IR, Thellufsen JZ, Sorknæs P, Korberg AD, Chang M, et al. The role of sustainable bioenergy in a fully decarbonised society. Renew Energy 2022. https://doi.org/10.1016/J.RENENE.2022.06.026.
[68] BBC News. Hinkley point C delayed by a year as cost goes up by £3bn. BBC News; 2022. https://www.bbc.com/news/uk-england-somerset-61519609 [accessed October 17, 2022].

[69] World Nuclear News. Fresh delay to Flamanville 3 blamed on pandemic. World Nuclear News; 2022. https://world-nuclear-news.org/Articles/Fresh-delay-to-Flamanville-blamed-on-impact-of-pan [accessed October 17, 2022].
[70] YLE News. Olkiluoto 3 reactor plugged into national grid, 13 years behind schedule. YLE 2022. https://yle.fi/news/3-12356596 [accessed October 17, 2022].
[71] International Energy Agency. Projected costs of generating electricity. Paris. 2020.
[72] International Energy Agency. Levelised cost of electricity calculator. https://www.iea.org/data-and-statistics/data-tools/levelised-cost-of-electricity-calculator; 2020 (accessed October 17, 2022).
[73] Lund H, Thellufsen JZ, Østergaard PA, Sorknæs P, Skov IR, Mathiesen BV. EnergyPLAN – advanced analysis of smart energy systems. Smart Energy 2021;1:100007. https://doi.org/10.1016/J.SEGY.2021.100007.
[74] Østergaard PA, Lund H, Thellufsen JZ, Sorknæs P, Mathiesen BV. Review and validation of EnergyPLAN. Renew Sustain Energy Rev 2022;168:112724. https://doi.org/10.1016/J.RSER.2022.112724.
[75] Paardekooper S, Lund H, Chang M, Nielsen S, Moreno D, Thellufsen JZ. Heat roadmap Chile: a national district heating plan for air pollution decontamination and decarbonisation. J Clean Prod 2020;272:122744. https://doi.org/10.1016/J.JCLEPRO.2020.122744.
[76] Campos J, Csontos C, Munkácsy B. Electricity scenarios for Hungary: possible role of wind and solar resources in the energy transition. Energy 2023;278:127971. https://doi.org/10.1016/J.ENERGY.2023.127971.
[77] Pastore LM, Lo Basso G, Cristiani L, de Santoli L. Rising targets to 55% GHG emissions reduction – the smart energy systems approach for improving the Italian energy strategy. Energy 2022;259:125049. https://doi.org/10.1016/J.ENERGY.2022.125049.
[78] Hansen K, Mathiesen BV, Skov IR. Full energy system transition towards 100% renewable energy in Germany in 2050. Renew Sustain Energy Rev 2019;102:1–13. https://doi.org/10.1016/J.RSER.2018.11.038.
[79] Bamisile O, Wang X, Adun H, Joseph Ejiyi C, Obiora S, Huang Q, et al. A 2030 and 2050 feasible/sustainable decarbonization perusal for China's Sichuan Province: a deep carbon neutrality analysis and EnergyPLAN. Energ Conver Manage 2022;261:115605. https://doi.org/10.1016/J.ENCONMAN.2022.115605.
[80] Xiong W, Wang Y, Mathiesen BV, Lund H, Zhang X. Heat roadmap China: new heat strategy to reduce energy consumption towards 2030. Energy 2015;81:274–85. https://doi.org/10.1016/j.energy.2014.12.039.
[81] Yuan M, Thellufsen JZ, Lund H, Liang Y. The first feasible step towards clean heating transition in urban agglomeration: a case study of Beijing-Tianjin-Hebei region. Energ Conver Manage 2020. https://doi.org/10.1016/j.enconman.2020.113282.
[82] Lund H, Kempton W. Integration of renewable energy into the transport and electricity sectors through V2G. Energy Policy 2008;36:3578–87. https://doi.org/10.1016/j.enpol.2008.06.007.
[83] Nielsen S, Hansen K, Lund R, Moreno D. Unconventional excess heat sources for district heating in a national energy system context. Energies (Basel) 2020:13. https://doi.org/10.3390/en13195068.
[84] Sorknæs P, Nielsen S, Lund H, Mathiesen BV, Moreno D, Thellufsen JZ. The benefits of 4th generation district heating and energy efficient datacentres. Energy 2022;260:125215. https://doi.org/10.1016/J.ENERGY.2022.125215.
[85] Hansen K, Connolly D, Lund H, Drysdale D, Thellufsen JZJZ. Heat roadmap Europe: identifying the balance between saving heat and supplying heat. Energy 2016;115:1663–71. https://doi.org/10.1016/j.energy.2016.06.033.
[86] Danish Energy Agency. Technology Data-Energy Plants for Electricity and District Heating Generation. 2022.
[87] Thellufsen JZ, Lund H. Fakta om Atomkraft. Https://WwwEnergyplanEu/Atomkraft/; 2023.
[88] International Energy Agency. Statistics questionnaires FAQ. Https://WwwIeaOrg/Statistics-Questionnaires-Faq; 2023. https://www.iea.org/statistics-questionnaires-faq [accessed March 26, 2024].