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Smart energy Denmark. A consistent and detailed strategy for a fully decarbonized society

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A R T I C L E I N F O

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A B S T R A C T

This paper presents a strategy for achieving a fully decarbonized Danish energy system (including transport and industry) in 2045. The strategy could also be relevant for most countries at a global level. The energy system analysis includes hour-by-hour computer simulations leading to the design of a Smart Energy System with the ability to balance all sectors of the complete energy system. In the analysis, issues such as international shipping and aviation, the sustainable use of biomass, and the exchange of electricity and gas with neighbouring countries are all considered. Moreover, the energy system is coordinated with other sectors to achieve a fully decarbonized society. Finally, the size of the employment impact of investing in decarbonizing the Danish economy is discussed.

1. Introduction

The wish to reach a fully decarbonized society is high on the political agenda to meet the Paris Agreement's goal of limiting the long-term increase in average global temperatures to 1.5 °C. As pointed out by the International Energy Agency [1], reducing global carbon dioxide (CO_2) emissions to net-zero by 2050 is consistent with such efforts. The energy and transport sectors – in sum called the energy system - account for around three-quarters of today's greenhouse gas emissions and, therefore, hold the key to any strategy for achieving a fully decarbonized society. However, strategies for reducing CO_2 emissions from fossil fuels in the energy and transport sector would have to align with reducing climate gas emissions in other sectors as well. This coordinated action calls for an integrated approach in which the interactions between the sectors in question are taken into consideration.

Moreover, the global goals cannot be reached without active contributions from every region and country. The individual countries would also have to coordinate their efforts to properly address common issues such as the decarbonization of international shipping and aviation, the global use of sustainable biomass resources, and the international exchange of electricity as well as – potentially – hydrogen and other green fuels.

Previous studies proposing decarbonization strategies for the energy system transition have focused both on analysing the decarbonization of specific sectors as well as fully decarbonized energy systems including all energy end-uses. In the case of the former, these have traditionally targeted the decarbonization of the power sector with the heating, transport, and industrial sectors included to a lesser extent [2]. On the other hand, decarbonization scenarios with 100% renewable energy, including all sectors, have been proposed at the transnational level for Europe [3], and on the national level for among others Germany [4] Finland [5], Sweden [6], Macedonia [7], Philippines [8] and Kazakhstan [9], as well as on the regional level for the south East Europe [10] the Åland Islands [11] and Akita, Japan [12], and at the urban scales for Bolzano, Italy [13] and Aalborg, Denmark [14]. In sum, this shows a trend towards a still better and more adequate understanding of the implications of a fully decarbonized 100% renewable energy society. However, these analyses must be placed within a broader global context of the energy transition, in which the availability and sustainable use of scarce resources, like biomass, should be adequately considered.

At the European level, Connolly et al. [3] address such concerns in their scenario development by limiting the amount of bioenergy in a 100% renewable system to a sustainable level while prioritizing its use in key sectors. At a national level, it has been demonstrated that 100% renewable energy systems can be achieved with the use of domestic renewable resources and energy savings for Germany [4], Finland [5], Macedonia [7] and Sweden [6], among others. However, higher

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List of abbreviations:

4GDH	4th Generation District Heating
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CHP	Combined Heat and Power
CO2	Carbon Dioxide
EV	Electric Vehicle
HTL	HydroThermal Liquefaction
IDA	(Ingeniørforeningen I Danmark) Danish Society of Engineers
IPCC	International Panel of Climate Change
LULUCF	Land Use, Land Use Change and Forestry
PtX	Power-to-X
PV	Photovoltaics

utilisation rates of some energy sources, like biomass, may be of concern when approaching their technical limits or when considering their use to meet non-energy demands.

At the local level, Thellufsen et al. [14] consider local demands and local constrained resources in a city decarbonization strategy by applying the share of biomass to be used by the local region in relation to the national, European, and global sustainably available resources. In this paper, unlike in typical analyses, transport demands cover the local demand combined with an estimated share of transnational transport, transit, international aviation and shipping. This type of strategic approach could be applied and scaled up to a national level and coordinated at a transnational or global level.

As described above, even though different attempts have been made, there is still a research gap in the development of coherent and consistent strategies for the proper design of fully decarbonized societies at the national level when taking the international context into consideration. This paper presents and calculates in detail a national strategy for decarbonizing the energy sector. This is done while considering the need for coordinating with other greenhouse gas sectors, as well as coordinating internationally with the rest of Europe, and in the end, with the rest of the world. The paper builds on the concept of Smart Energy Systems by focusing significantly in more detail on bioenergy and biomass pathways as well as including carbon capture and storage (CCS) in combination with carbon capture and utilisation (CCU) [15].

The focus in this paper is on the general and fundamental guidelines for the design of a transition strategy for a country to become a fully decarbonized society. To demonstrate such general guidelines, we have applied them to the case of Denmark by the year 2045.

Since 2016, shifting Danish governments with the support of a vast majority in Parliament have aimed at achieving first a fully renewable and then a fully decarbonized society. Recently, in 2020, the Danish government passed a Climate Law through Parliament aiming for a 70% reduction in Danish greenhouse gasses by 2030 and a fully decarbonized society by 2050 [16].

The climate law and action plan include the following items:

1. Energy savings in among others public buildings
2. A national strategy for sustainable buildings
3. A strategy for electrification of transport, industry and society in general
4. More funds for research and demonstration projects
5. An assessment of Danish and North Sea countries' mutual expansion of offshore wind
6. An investigation of an energy island of 10 GW wind before 2030
7. Supporting afforestation (new forest)
8. Climate adoption via coordination of coastal protection

Various proposals and strategies from different stakeholders on how best to implement these political goals have been put forward and discussed as part of the political process. This paper describes one of these proposals, which was made by some of the authors of this paper in close collaboration with the Danish Society of Engineers (IDA). The proposal is called IDA's Climate Response 2045 [17]. This represent the idea of a Smart Energy Denmark in 2045, thus for this paper it will also be referenced as Smart Energy Denmark 2045. One of the focus points in this study has been to show how a fully decarbonized society could be reached before 2050, i.e., in 2045.

The study represents an interesting case, as it presupposes a significant change in the energy, industry and transport sectors already by 2030. Thus, the paper analyses and discusses a strategy that can fulfil the short-term goal in the next decade, and furthermore takes the 2030 scenario as the offset for achieving carbon neutrality in a Smart Energy Denmark 2045. This makes it possible to discuss how ambitious 10-year goals could work as a stepping stone towards eliminating fossil fuel by the mid-century.

2. Methodology: how to achieve and evaluate a strategy for a decarbonized Denmark by 2045

Smart Energy Denmark 2045 is another stepping stone in a long history of communicating technical strategies for the renewable energy transition in the Danish energy and climate debate. Thus, proposals to a decarbonized future have already been put forward in a close collaboration between researchers from Aalborg University and IDA as early as in 2006 [18] and later, in 2009 [19] and 2015 [20].

Already in 2006, the conclusion was that a 100% renewable energy supply based on domestic resources would indeed be physically possible for Denmark and that significant steps towards this goal would be feasible already well before 2030. However, achieving the goal of a future 100% renewable energy system is a very complex process. On the one hand, a wide variety of measures need to be combined to reach the target, and, on the other hand, each individual measure would have to be evaluated and coordinated with the entire energy system.

In 2006, the process of developing a qualified response to the present and future challenges was successful in combining energy systems analysis with inputs and feed-back from experts. Proposals within subsectors were adjusted to fit well into the overall system, in terms of technical innovation, efficient energy supply and socio-economic feasibility.

The making of Smart Energy Denmark 2045 was based on a similar but more limited working process involving experts in different technical areas in a back-and-forth dialogue with energy systems modelling of the role of individual technologies into an overall solution.

Already in the 2006 study, it was highlighted that Denmark would have to consider to which degree the country should rely on biomass resources, which would involve the use of farming areas, or mostly on wind power, which would involve a large share of hydrogen or similar energy carriers leading to certain inefficiencies in the system design. The new study also maintains a focus on this exact issue.

A country may convert to 100% renewable energy and/or fully decarbonize in different ways. In the previous studies, the aim was to identify meaningful, doable and affordable strategies. Those studies have made it clear that the transition to a fully-fledged renewable society requires the fulfilment of the two following criteria or governing principles:

Firstly, Denmark would have to fulfil its objectives of increased renewable energy and CO_2 reductions in a way that would fit well into a context in which the rest of Europe – and the world – realistically would be able to do the same.

This overall criterion would imply several choices and issues. Some of the most important are that:

- Denmark should include the Danish share of ***international aviation and shipping*** even though it is not yet included in the UN method for calculating the Danish CO_2 emissions.
- Denmark should not exceed the Danish share of ***sustainable use of biomass*** in the world.
- Denmark should make its contribution in terms of ***flexibility and reserve capacity*** that would allow for the increased integration of non-continuous RES, mainly wind and solar, into the ***European electricity supply.***

Secondly, Denmark should fulfil its objective of a 70% CO_2 reduction in 2030 in a way that would fit well into a fully decarbonized society by 2045. To fulfil this principle, existing technologies should be combined with paving the way for the right technologies in the long term. Therefore, before 2030, politicians, the public administration, and private firms would need to prioritize:

- Energy technologies which fit well into the future zero carbon solutions, as expanded on in chapter 3.
- Innovation efforts for technologies that would be needed after 2030, even if they are not likely to play a significant role before 2030.

The question is, of course, what could make the Danish society move in this direction. A doable and affordable strategy would be to head for a Smart Energy System. The idea of this concept is to provide the scientific basis for a paradigmatic shift away from single sector thinking towards a coherent and integrated understanding. Focus is on how to design and identify the most achievable and affordable strategies to implement future fully decarbonized energy systems as first introduced in 2012 [21]. The Smart Energy System was defined in a book in 2014 [22], after being pre-published in a booklet from 2013 [23].

As explained in Ref. [24], the core idea of the Smart Energy Systems approach is to identify potential synergies between sub-sectors. The hypothesis is that the most effective and least-costly solutions are to be found in combining the sub-sectors with one another, utilising not only electricity grids, but also heating, cooling and gas grids. Thus, a Smart Energy System goes beyond a simple sector integration and emphasises the need for integrating grids. The approach does not only look at power to heat, gas and fuel, but for instance also at utilising excess heat production from industry and e-fuels in the district heating grid.

One main point is that the analysis of individual technologies and sectors is contextual and, to do a proper analysis, one must define the overall energy system in which the infrastructure should operate. Another main point is that different sub-sectors influence each other, and one must take such influence into consideration if the best solutions are to be identified.

To make the IDA's Climate Response strategy more detailed and operational, the costs of each element have been simulated by using advanced hour-by-hour modelling as an integrated part of the working process. This has been carried out through extensive use of the advanced energy system analysis tool EnergyPLAN (version 15.1 and 16) [25]. Applying this tool involves the following benefits:

- Other researchers can replicate the calculations. The EnergyPLAN tool is free of charge and user-friendly. It can operate on a normal computer and does not depend on any additional solvers or similar. Together with input data used in this study, it can be downloaded from the homepage https://www.energyplan.eu/ida2045/ [26].
- The tool is very credible. The model has been and is widely used, and already in 2015 it was used in more than 100 peer-reviewed research articles [27]. This number has now increased to more than 300 [28]. The application of the model includes energy systems analysis and modelling at the European level [3] as well as at the national level for countries such as Romania [29], Ireland [30], Croatia [31], Jordan [32], China with a focus on heat [33] wind [34] or transport [35], Serbia [36], Finland [37], Iran [38], and Denmark with a focus on heat and power [39] or infrastructures [40].
- EnergyPLAN is suitable for the analysis of Smart Energy Systems in accordance with its theory and concept [22]. Thus, the tool includes a comprehensive list of relevant sectors, grids and storage options as well as relevant conversion units between the different energy sectors [41].
- EnergyPLAN makes detailed hourly calculations. The tool allows for hourly time resolution and chronological calculations of storage and grid infrastructures. The calculation of storage utilisation ensures the creation of chronological results in which the use of different storage options is documented for charging, discharging and content on an hourly basis.

A comparison of the EnergyPLAN tool with other models is presented in Ref. [42]. A full description and documentation of the model can be found in Ref. [25]including discussions and descriptions on how the tool applies to the Smart Energy Systems approach and concept [24]. Moreover, theoretical considerations concerning optimization versus simulation tools are presented in Ref. [43] and the problem of how to cope with uncertainties in future fuel and electricity prices is described in Ref. [44].

3. Analysis and results: smart energy Denmark 2045 and the 2030 scenario

The concrete proposals of Smart Energy Denmark 2045 have been divided into four sectors and designed with a focus on five crosscutting areas.

The four sectors are:

- Heating and Cooling: Supply of heat for all buildings
- Industry: Service, commercial and heavy industry, including gas and oil in the North Sea
- Transport: Persons and goods including aviation and shipping
- Electricity: Primarily, the classic electricity consumption including the overall balancing of the electricity supply

Five crosscutting focus areas following from the two main criteria are:

- Energy Efficiency: Including the fulfilment of the EU Energy Efficiency Directive.
- Sector integration: Including energy storage, conversion and electrification, as well as the integration between electricity, gas, district heating and cooling grids.
- Biomass: With a focus on the issue of sustainable biomass
- Renewable energy: Which type and how much of it?
- Technological challenges: Identifying the most important technologies as well as their potential role in 2030 and 2045 based on their expected development

The Smart Energy Denmark transition path towards 2045 is described in the following with a focus on the four sectors and five focus areas.

3.1. Denmark 2020

As a benchmark, a Sankey diagram illustrates the current situation in Denmark (2020) in Fig. 1. As can be seen, Denmark already has a high input of wind power equivalent to approx. 50% of the electricity supply as well as a high share of biomass. However, the share of fossil fuels in terms of coal, oil and natural gas is still substantial. Especially, within the transport sector and manufacturing, the share of fossil fuels is relatively high compared to the other sectors.

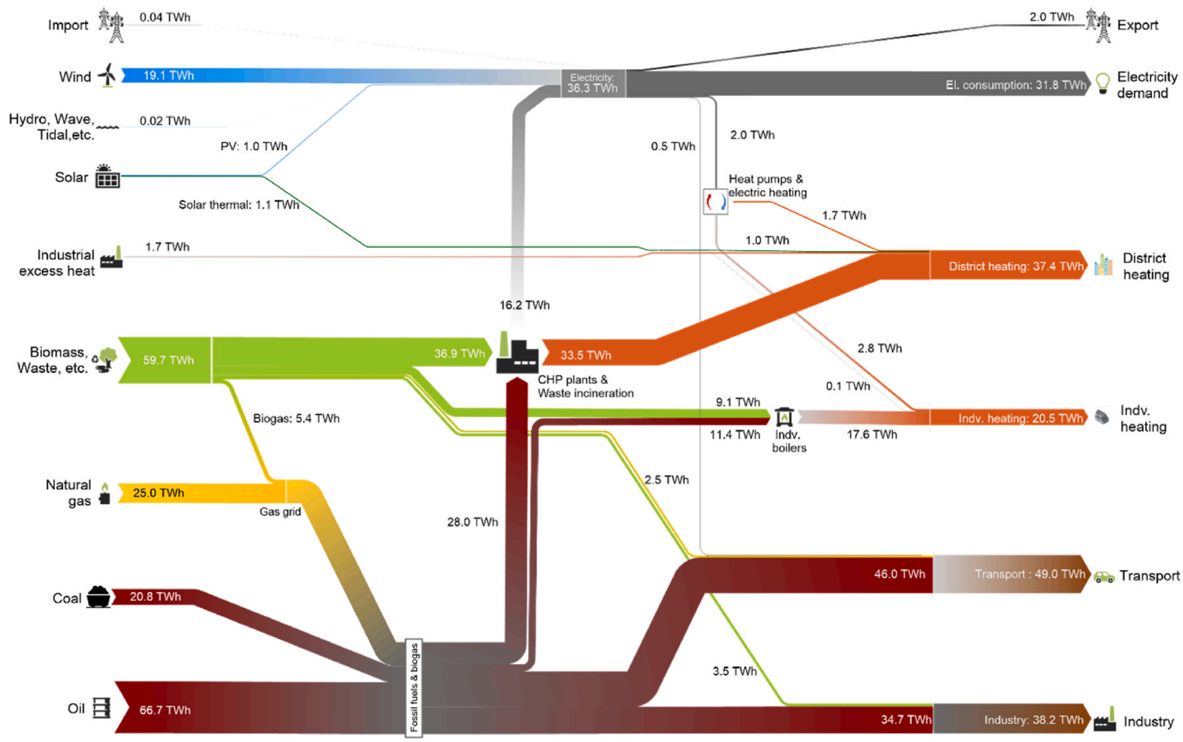

Fig. 1. Sankey diagram of the Danish Energy System 2020.

3.2. Denmark 2030 and 2045

As described above, the concrete proposal has been developed in a back-and-forward collaboration between expert technology inputs and energy systems analysis leading to the suggestion of several detailed proposals condensed in the following list. A full and detailed description of the proposal can be found in Ref. [17]. The transport sector is more discussed in Kany et al. [45]:

Energy efficiency (including fulfilment of EU Energy Efficiency Directive):

•Heat savings in all existing buildings (resulting in average savings of 12% in 2030 and 30% in 2045 as compared to 2020).
•Gradual transition to 4th generation district heating (half in 2030, full in 2045), which will both reduce the grid loss of the district heating system while also improving the efficiency of the energy conversion units and allowing for increased utilisation of waste heat from industrial processes [46].
•12% savings and efficiency improvements in the industrial energy consumption in 2030 and 32% in 2045.
•More energy efficient technologies in data centres, resulting in a reduction in electricity consumption of 5%.
•Curbing of growth in private car mileage as compared with growth in the baseline projection (1.6%/yr instead of 2%/yr) and similar savings within modular shifts from car and aviation to trains and public transport.
•10% savings in the 'classic electricity consumption' in 2030 (20% in 2045), with more energy efficient energy technologies, such as more energy efficient appliances.

Sector coupling (storage, conversion and electrification):

•Oil and gas boilers phased out and replaced with a mix of district heating and individual heat pumps, depending on the heat density of the given area.
•District heating expanded to 63% of heating requirement using heat pumps, excess heat from industries, data centres and PtX technologies in combination with large-scale thermal storage. The remaining heating demand is supplied by individual heat pumps supplemented by solar thermal to reduce electricity demand, both connected to heat storages. The solar thermal corresponds to 16% of the yearly heating demand and the heat storage capacity corresponds to the heating demand of 1 average day.
•Balancing of wind, solar and wave power with flexible electricity consumption units. This mainly refers to smart charging electric vehicles that charge when it is suitable for the energy system, heat pumps connected to heat storages in individual households and district heating, and electrolysis plants from the other sectors, including the use of existing natural gas storage and the establishment of hydrogen storage.
•Electrolysis capacity is set at about 60–65% to allow for a flexible operation of the electrolysis with the utilisation of H_2 storage that is set to allow for about 4 days of storage of average production. This allows for increased utilisation of variable renewable electricity sources for PtX.

Biomass (kept at a sustainable level):

•Wood, waste and upgraded biogas to be used in CHP plants. In 2045, only waste and upgraded biogas, as to handle remaining waste products relevant for incineration and have flexible gas-fired CHP plants for backup and periods with low wind and PV potential.
•200 MW woodchip gasification (syngas and CO_2 for electrofuels) in 2030 and approx. 2000 MW in 2045, divided between gasification, HTL and pyrolysis.
•Biogas production to be increased to 35 PJ in 2030 and 60 PJ in 2045. The biogas will be upgraded by removing the CO_2 part that is then utilised for PtX processes.

Renewable energy:

•Solar heating in the district heating system and in individual dwellings to supplement heat pumps.
•Geothermal heat for district heating; 500 MW in 2030 increasing to 1000 MW in 2045.

- PV systems to be expanded from approx. 1000 MW in 2020 to 5000 MW in 2030, rising to 10,000 MW in 2045. The PV systems should primarily be on large roofs to reduce the land-use for PV systems.
•Onshore wind power to be expanded from approx. 4200 MW in 2020 to at least 4800 MW in 2030 and 5000 MW in 2045.
•Offshore wind power to be expanded from approx. 2000 MW in 2020 to 6630 MW in 2030, rising to nearly 14,000 MW in 2045.
•Wave power (132 MW) (but with wind as an alternative) in both 2030 and 2045.

The underlying principles of these proposals are:

- To make it possible to exploit technological positions of strength and to maximize the number of newly created jobs
- To promote and facilitate a technological development after 2030 bringing the Danish energy system closer to the goal of decarbonization in 2045
- To ensure a degree of energy efficiency in accordance with the EU directive on this issue
- Aiming at attaining the 70% CO_2 reduction objective by 2030 in a socio-economically efficient way
- And finally, to ensure a broad popular involvement in the implementation of these political goals

Additional to the Danish share of global sustainable biomass resources, the Smart Energy Denmark scenario is based on the use of substantial wind power and PV. This corresponds to similar scenarios for Europe [47] and other parts of the world such as e.g. Central and South America [48]. Since Denmark has good wind potential, it may likely be a future exporter of wind to other European countries with less wind potential.

In Fig. 2, the 2030 Scenario for the Danish energy system is summarized. As can be seen, the input of wind power, and – to some extent – also solar energy, will increase substantially. However, to reach a sustainable level, the amount of biomass would have to decrease. In 2030, the remaining fossil fuels would primarily be used in the transport sector, while in 2045, there would be no fossil fuels at all. In transport, priority will be given to the direct use of electricity in electric vehicles. However, liquid fuel would still be required to cover all the needs. Especially in 2045, when the Danish shares of international shipping and aviation are included, green fuels based on biomass and hydrogenation in combination with CCU are to become important technologies in a full decarbonization of the energy system.

In Fig. 3, the Danish energy system has moved on to 2045. The most important changes compared to 2030 are that fossil fuels are completely phased out and, therefore, the direct electrification of the heating and transport sectors plays a major role in combination with electrofuels.

In both 2030 and 2045, the Smart Energy Denmark scenario will exchange electricity with neighbouring countries based on the principle of mutual benefits, e.g., by providing electricity from wind power to Norway to reduce the use of water in the relatively large dammed hydro power capacity in Norway. Export occurs when there is an excess of variable renewable electricity production in the modelled energy system, and import occurs when there would be a need for power plant operation. The scenario does not include scenarios for the rest of Europe, but instead limits these import and export potentials based on an assumed limit of the relative population of Denmark in relation to the total European population, modelled as an external storage capacity of 820 GWh. The scenario assumes a capacity of 6000 MW of interconnectors.

This section is split into three subsections, each discussing a key conclusion. The first concerns the question of sector integration, Smart Energy Systems and the change in the energy system from 2030 to 2045. The second discusses the reduction in CO_2 emissions, the need for full accounting of transport, including international shipping and aviation, and the third deals with the costs of this approach.

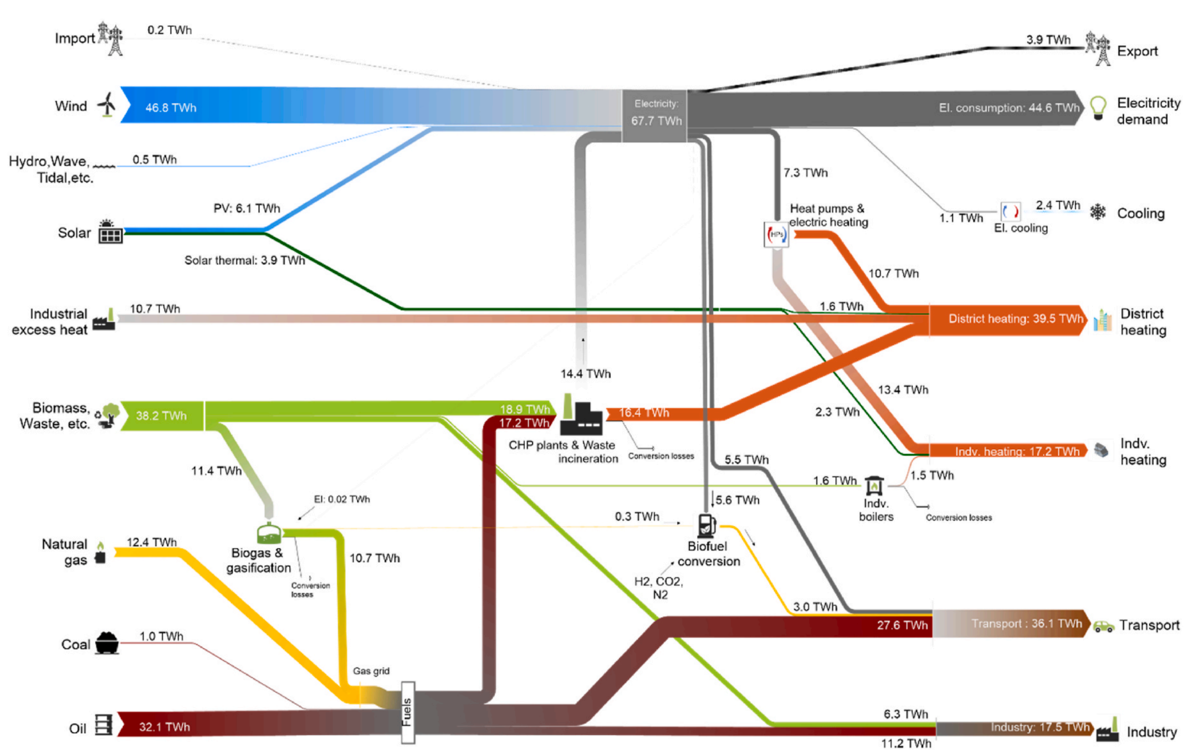

Fig. 2. Sankey diagram of the 2030 Scenario for the Danish energy system in accordance with the IDA 2030 proposal.

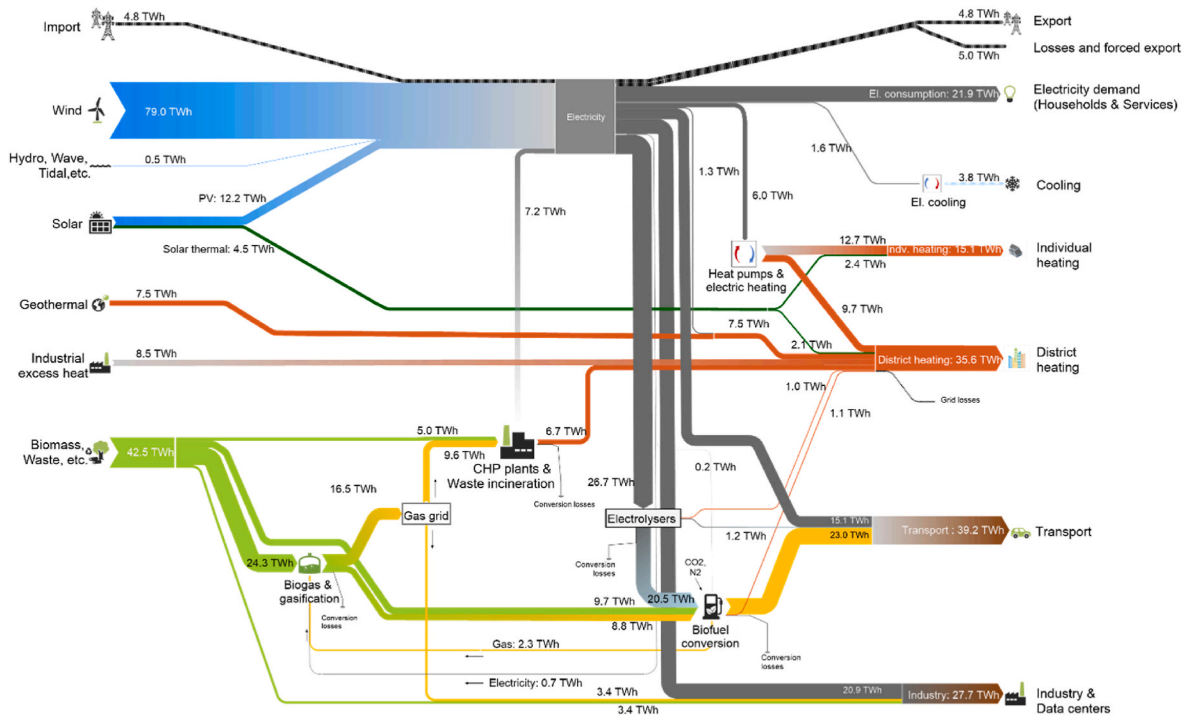

Fig. 3. Sankey diagram of the Smart Energy Denmark 2045 energy system in accordance with the IDA 2045 proposal.

3.3. Renewable energy and system design for 2030 and 2045

With the implementation of the Smart Energy System described in chapter 3, it is possible to achieve a fully renewable energy system. Fig. 4 synthesizes Figs. 1–3 into an overview of the primary fuel consumption in the system, while Fig. 5 shows the heating demand and production and Fig. 6 shows the electricity demand and production units implemented in the systems, both in 2030 and 2045.

The results reveal that through the implementation of a Smart Energy System it is possible to achieve a fuel-efficient transition to a 100% renewable, decarbonized energy system in 2045. Furthermore, it is demonstrated that it would be possible to design an energy system in 2030 that not only fulfils the 70% reduction target, but also serves as a stepping stone towards the fully decarbonized energy system in 2045.

3.4. Carbon targets and carbon emission reduction

The Danish political target of a 70% reduction in greenhouse gasses is defined in accordance with the UN and IPCC accounting methodology, having 1990 as the point of departure. Fig. 7 illustrates the development in Danish emissions since 1990 divided into the different sectors: energy and transport, agriculture, process, additional and land area. In 1990, emissions were equivalent to 75.7 Mt CO_2, and these had been reduced to a little less than 50 Mt CO_2 in 2020. As in the rest of the world, the highest share comes from the energy and transport sectors. An investigation of other sectors shows that the emissions of the energy and transport sectors should be reduced to approx. 11.5 Mton CO_2 by 2030 for the 70% reduction target to be achieved. The energy system achieves this goal by 2030 as illustrated in Fig. 7. Fig. 8 illustrates the Danish greenhouse emissions of the energy and transport sectors divided into the four sectors of the IDA's Climate Response proposal. As can be seen,

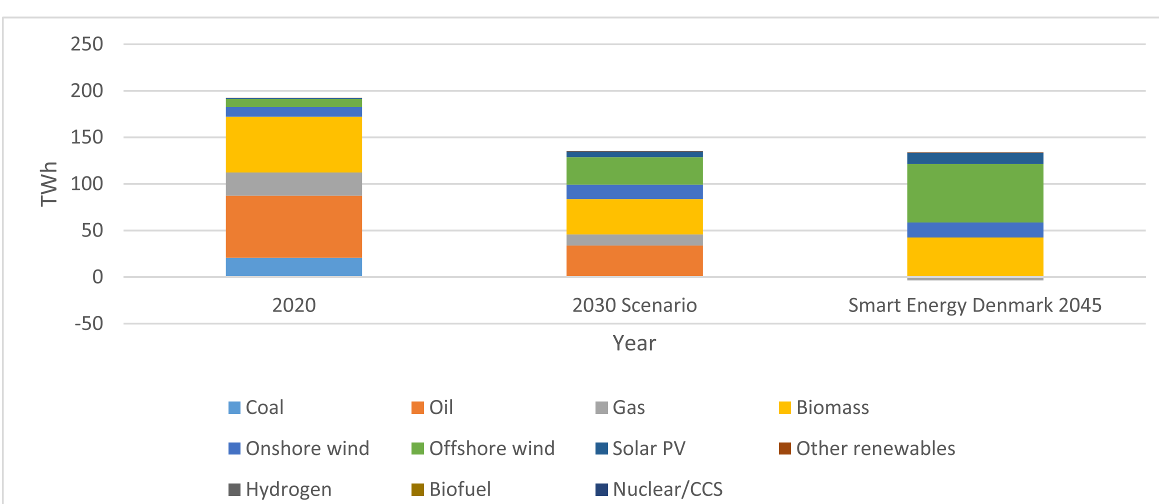

Fig. 4. Primary sources of energy in 2020, 2030 and 2045.

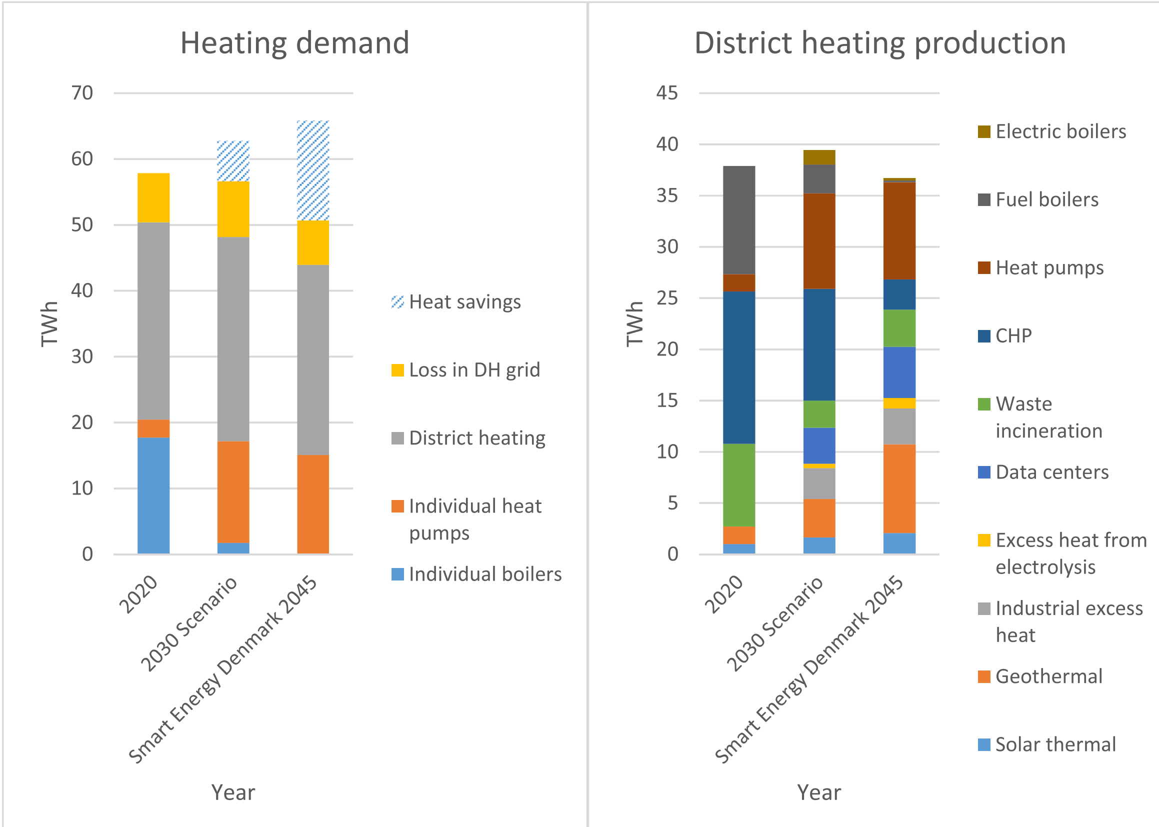

Fig. 5. The demand for and production of heating in 2020, 2030 and 2045.

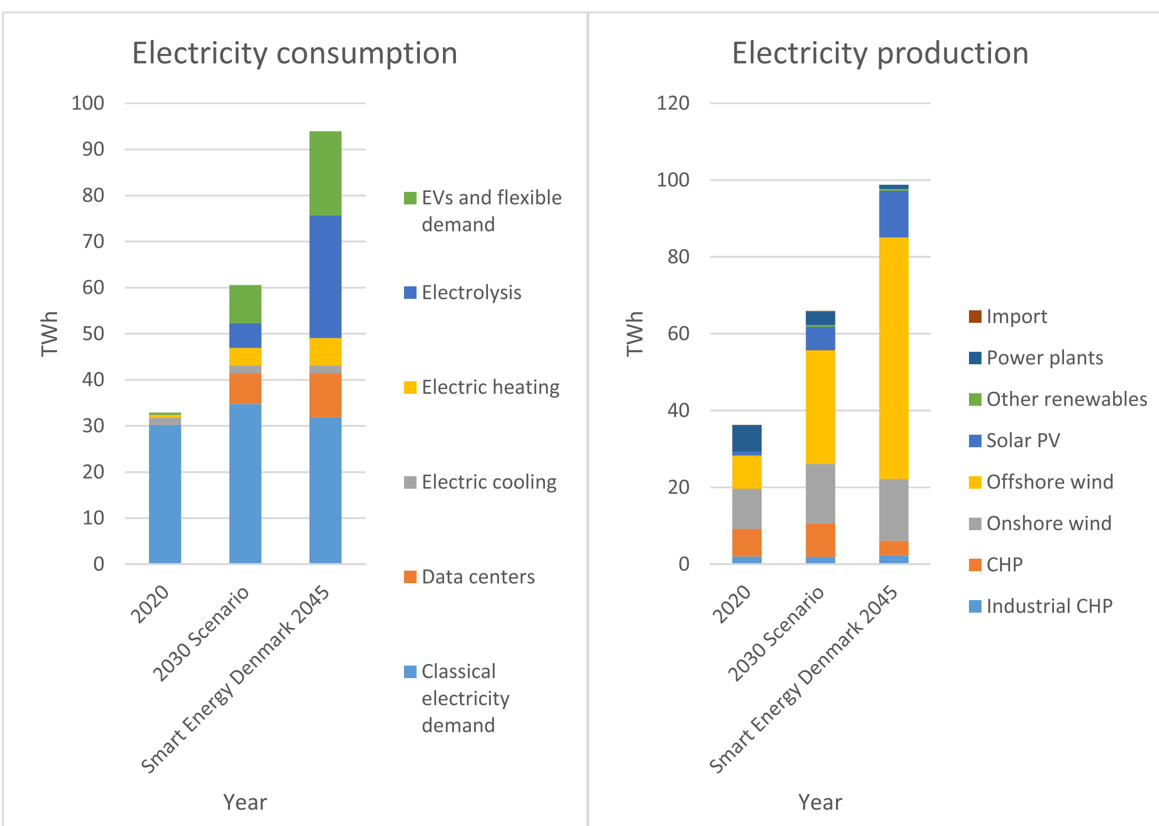

Fig. 6. The demand for and production of electricity in 2020, 2030 and 2045.

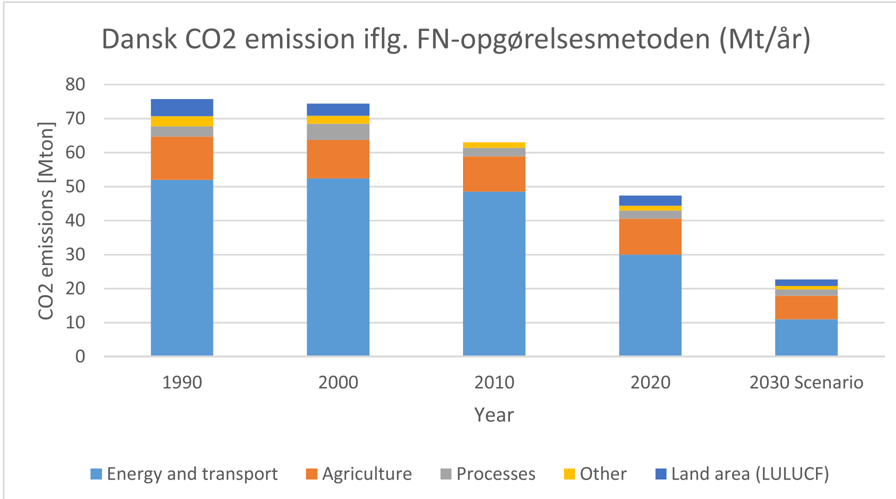

Fig. 7. Danish greenhouse gas emissions in CO_2 equivalent since 1990. IDA's Climate Response proposal will reduce emissions by 70% in 2030 Scenario. The numbers do not include international shipping and aviation.

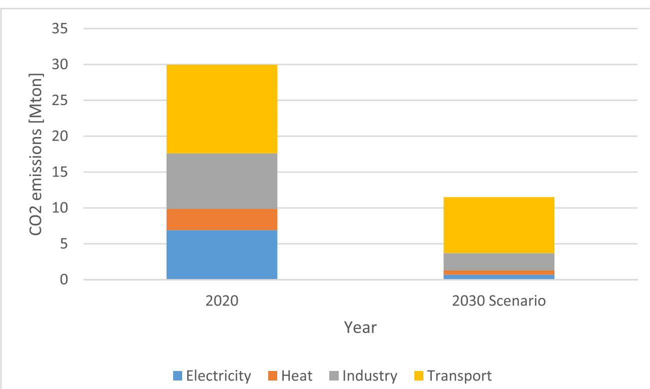

Fig. 8. Danish greenhouse gas emissions divided into the four sectors of IDA's Climate Response proposal highlighting the 2030 Scenario.

the major challenge is to be found within the transport sector.

The Danish emissions shown in Figs. 7 and 8 are accounted for with reference to the criteria defined by the UN International Panel of Climate Change (IPCC). For each member state, the accounting is made with reference to the Kyoto and UNFCCC obligations originating directly from activities in the land in question. This includes stationary plants and domestic transport, but not international transport.

Fossil fuel emissions are attributed to the country in which it is being burned, while emissions in relation to the production of biomass, on the other hand, are accounted for in the country of origin. Biomass emissions are part of the LULUCF sector, i.e., Land Use, Land Use Change and Forestry.

In the Smart Energy Denmark 2045 scenario, not only domestic transport should be included. To achieve a fully decarbonized society, Denmark would have to include the Danish share of international shipping and aviation. In the UN system, the Danish share in 2020 is identified to be 11.6 TWh for international aviation and 6.9 TWh for international shipping [17].

If the greenhouse gasses from these sectors are included, the situation changes quite a bit, as illustrated in Fig. 9.

Thus, the Smart Energy Denmark 2045 scenario allows for a full decarbonization of the energy sector, but further decarbonization of the rest of the society is necessary. To achieve complete climate neutrality, several emissions are expected to remain in 2045. Primarily, these come from agriculture, industrial processes, flight contrails, and from the

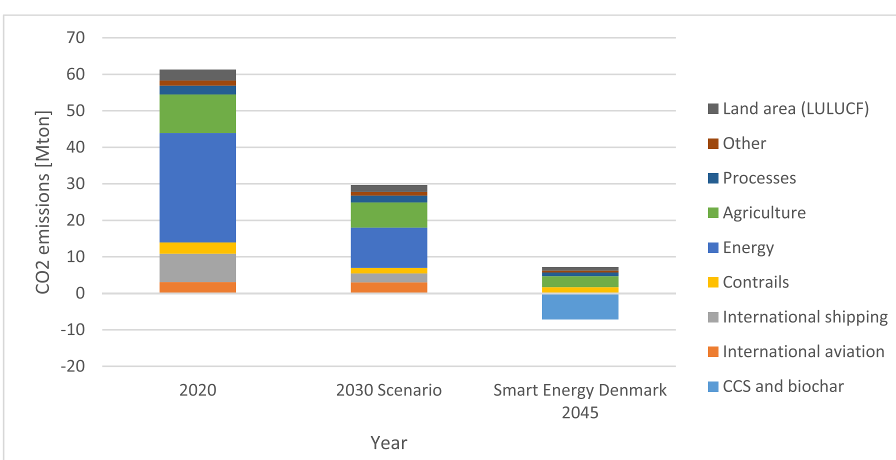

Fig. 9. Danish greenhouse gas emissions in CO_2 equivalent when including the Danish share of international shipping and aviation. To achieve a fully decarbonized society in Smart Energy Denmark 2045, the proposal includes CCS and Biochar to compensate for the remaining emissions in the other sectors than energy and transport, as well as greenhouse gas equivalents arising from contrails in aviation.

burning of bio and e-fuels. To limit these emissions, the Smart Energy Denmark 2045 scenario suggests carbon capture, both through biochar from pyrolysis and by point capture from industry and power stations. The implementation of CCS and biochar is done based on the principle that carbon capture should be used as a final abatement step and not to mitigating fossil fuel use in industry, transport or power production. The purpose of CCS and bio sequestrations is to offset non-avoidable carbon emissions from industry and transport, for instance from the chemical process of producing cement or contrails from shipping. A detailed description of the biomass and CCUS part of the proposal is given in Ref. [49].

3.5. The energy system costs of smart energy Denmark 2045

So far, focus has been on technological possibilities. The next elements to be investigated here are the resulting costs of the 2030 Scenario and Smart Energy Denmark 2045 systems. With these changes to the energy system, many investments would have to be made. Table 1 shows the main investments, targeted at 2030 and 2045, respectively. The calculation of cost is based on a comprehensive cost database, primarily using consensus investment data from the Danish Technology catalogue [50]. For a few technologies - not included in the catalogue - costs are based on relevant literature. A full identification of all cost data can be accessed by downloading the EnergyPLAN input data files from the following website: https://www.energyplan.eu/ida2045/.

When combining the increase in investments in the energy sector with lower fuel costs, it is possible to assess the total energy system costs. These are represented in Fig. 10. When comparing the costs in the table, it is important to mention that only the 2045 scenario includes international shipping and aviation.

From Fig. 10, a 100% renewable decarbonized system is possible to achieve, and not at an increased cost, compared to the reference scenario

Table 1
Investments to be made from 2020 to 2030 and 2030–2045.

	From 2020 to 2030		From 2030 to 2045	
	Investments	Yearly costs	Investments	Yearly costs
	Billion DKK	Million DKK/year	Billion DKK	Million DKK/year
Building renovations	124	5360	185	7986
Onshore and offshore wind	78	4173	102	5150
EVs and e-roads	73	6896	52	4947
Individual heat pumps	70	5114	7	946
Industry (savings and electrification)	36	2570	28	2079
District heating expansion and 4GDH	30	1467	7	462
Solar PV	21	937	22	969
Biogas plants	18	1223	12	857
New gas power plants	16	897	1	18
EV charging, distribution grid and ITS	14	825	25	1463
Large-scale heat pumps	9	499	28	1594
Electrolysis and H2 storage	8	501	78	3531
Geothermal energy	8	440	8	410
Wave power	5	303	5	303
Gasification, pyrolysis and e-fuels	5	316	25	1579
Intelligent flexible electricity demand	3	235	1	93
Solar thermal, excess heat and thermal storage	3	176	2	97
District cooling	2	89	0	0
Gas and hydrogen grid	2	89	10	390
Sum	**525**	**32,110**	**598**	**32,874**

in 2045. In terms of cost, the 2030 Scenario is also like a 2030 baseline. However, due to expected population and demand growth, the overall annual cost for the energy system will increase when looking at the period from 2020 to 2045 no matter if the smart energy Denmark scenario or the reference is implemented. While the direct cost is the same, the cost structure makes an important difference. The smart energy Denmark scenario replaces fuel costs by investment costs. Such a change constitutes an important possibility to increase domestic economic growth and job creation as further detailed in the following.

3.6. Employment effects in 2030 – a brief review of previous employment studies of the Danish economy

The employment effects of investing in smart energy systems are important as most EU countries suffer from a shortage of workplaces and a far too high unemployment. However, the Danish economy is in the peculiar situation that there has been, is and probably also will be a future shortage of labour. In both cases estimates of possible employment effects convey something about the degree of restructuring needed to promote decarbonization.

Studies of the employment effects are estimates - either historical or future-oriented - and very different methods have been applied internationally. Concerning specific estimates for the Danish economy most of the few studies have been prognoses. In a very early prognosis by one of the present authors [51], it was predicted that employment would increase by *17,*000 by 2015 if a so-called Green Energy plan was implemented.

A comparative and historical input-output study by Markandya et al. (2015, p. 1347) [52] suggested that employment from 1995 to 2009 due to ‘changes in the input structure of the EU electricity and gas sector’ - indicating restructuring and decarbonization - had created *9800 additional jobs* but for a smaller part of the Danish economy than in Ref. [51].

Much higher estimates were demonstrated, as part of ‘IDA’s Climate Response 2045′, by The Economic Council of the Labour Movement (Arbejderbevægelsens Erhvervsråd). They attempted to estimate the possible employment effects of making the above-mentioned investments. The result of this work was reported in two separate notes. The main paper [53] stipulates that within 10 years the investments would create as much as *390,000 full-time jobs*; 40% of these would be created within work and construction as a crucial part of the general strategy is to renovate existing buildings. In the supplementary analysis [54], the employment effects of investing in power-to-X-technologies are estimated independently. Such an investment is expected to increase the employment by *22,000* additional full-time jobs within 10 years; almost half of which would be established within the manufacturing sector. Compared to the studies reviewed above, 390,000 is an upper hand estimate and it would be impossible to adjust the economy to such a large number without a major restructuring of the economy.

4. Conclusion

In this paper, we have discussed and presented a set of ***guidelines*** for the design of a transition strategy for a country to become a fully decarbonized society, and we have applied it to ***the case of Denmark*** by year 2045.

As a core element of the guidelines, a country would have to fulfil its objectives of increased renewable energy and CO_2 reductions in a way that would fit well into a context in which the rest of the world realistically would be able to do the same. Moreover, a country should fulfil its short-term objective of CO_2 reduction in a way that would be able to lead to a fully decarbonized society as a next step. These overall criteria imply several choices and issues. Some of the most important are to include the country share of *international aviation and shipping* and not exceed the country share of a global *sustainable use of biomass*, as well as enabling the country’s contribution in terms of *flexibility and reserve*

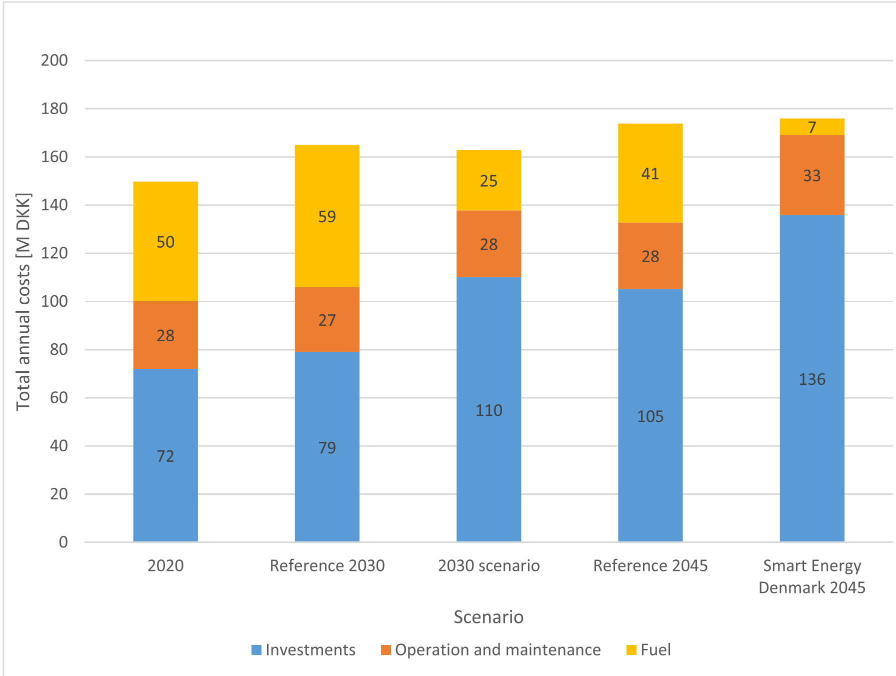

Fig. 10. Socio-economic cost of transforming the economy in 2020, 2030 and 2045.

capacity to increase the integration of non-continuous RES such as wind and solar into the electricity supply. Finally, countries should include innovation efforts for technologies that would be needed in the long-term, even if these are not likely to play a significant role in the short term.

An additional and essential part of the guidelines is to base the design of the strategy on the smart energy systems principles of taking a cross-sectoral approach to identify a cost-efficient, technically liable and politically doable solution.

These guidelines have been applied to ***the case of Denmark*** in the year 2045. The energy system analysis includes hour-by-hour computer simulations leading to the design of a Smart Energy System with the ability to balance all sectors of the complete energy system. In the analysis, issues such as international shipping and aviation, the sustainable use of biomass, and the exchange of electricity and gas with neighbouring countries are all considered. Moreover, the energy system is coordinated with other sectors to achieve a fully decarbonized society. Finally, the possible employment impact of investing in decarbonizing the Danish economy is discussed.

The key findings of the case are that a fully decarbonized Danish society by 2045, including Denmark's share of international aviation and shipping, is technically doable within the limitations of Denmark's share of sustainable biomass resources in the world. Compared to a business-as-usual reference, the societal costs do not have to increase. However, the costs of importing fossil fuels are replaced with investment costs and thus raise lead to increasing employment and economic growth. In the present situation, there is, however, a labour shortage in the Danish economy in several sectors. But in many other countries, the situation is different, and in the longer run, the benefits of new types of employment and a greener industrial development would also be crucial to the general Danish future economic development.

Hence, in the paper, we argue that a green transition of the Danish economy and society is doable, economically responsible, but also realistic within a sufficiently ambitious deadline. However, this does not necessarily imply that it would also happen. It would require decisive long-term public investments in a green transition of the entire energy system and that the private sector is encouraged to follow suit and decides to do so. The challenge is also to coordinate the many larger and smaller private and public initiatives to go green, thus enabling the decarbonization of not only the Danish but also the European energy system.

Credit author statement

Henrik Lund: Conceptualization, Methodology, Data curation, Formal analysis, Writing - original draft, Writing – review & editing. **Jakob Zinck Thellufsen**: Methodology, Data curation, Formal analysis, methodology, validation, Writing – review & editing. **Peter Sorknæs**: Methodology, Data curation, Formal analysis; validation. **Miguel Chang**: Visualization, Writing – review & editing. **Poul Thøis Madsen**: Formal analysis, Writing – review & editing. **Brian Vad Mathiesen**: Conceptualization, Methodology, Writing – review & editing. **Mikkel Strunge Kany**: Data curation; Writing – review & editing. **Iva Ridjan Skov**: Methodology, Visualization, Writing – review & editing.

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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