100% Renewable Energy Systems in Project Future Climate

the case of Denmark

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100% renewable energy systems in project Future Climate - the case of Denmark

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ABSTRACT

Greenhouse gas mitigation strategies are generally considered costly with world leaders often engaging in debate concerning the costs of mitigation and the distribution of these costs between different countries. In this paper, the analyses and results of the design of a 100 per cent renewable energy system by the year 2050 are presented. Two short term transition target years in the process towards this goal are analysed for 2015 and 2030. The analyses reveal that implementing energy savings, renewable energy and more efficient conversion technologies can have positive socioeconomic effects, create employment and potentially lead to large earnings on exports. If externalities such as health effects etc. are included, even more benefits can be expected. 100 per cent renewable energy systems will be technically possible in the future, and may even be economically beneficial compared to the business-as-usual energy system. Hence the current debate between leaders should reflect a combination of these two main challenges.

1. INTRODUCTION

While some world leaders emphasise that the financial crisis is a showstopper regarding the mitigation of greenhouse gasses, others contend that this is a golden opportunity to make these changes and create new jobs, which are not based on the notion of abundant fossil fuels. The Danish case shows that a lot can be done with existing technology while ensuring economic growth and developing new industries [1]. The question then becomes, what consequences might arise as a result of following a path towards a 100 per cent renewable energy system?

In analysing such energy systems, often only single technology groups are analysed, such as e.g. the technologies for wind integration: CHP plants, battery electric vehicles, fuel cell vehicles, electrolysers, heat pumps and thermal storages etc. [2-6]. Other studies often analyse island energy systems [7-12], or analyse the technical aspects of changes in total national energy systems while lacking e.g. the economic side [13;14].

In analysing 100 per cent renewable energy systems, energy savings, efficient conversion technologies and the replacement of fossil fuels with renewable energy are essential elements to consider [15-18]. The design of 100 per cent renewable energy systems has to meet two major challenges. One challenge is to integrate a high share of intermittent resources into the energy system, especially concerning electricity supply [5;19-21]. The other is to include the transportation sector in the proposed strategies [22;23].

In this paper, the possibilities to reduce the emission of greenhouse gasses by 90 per cent is analysed by using only renewable energy sources; related socio-economic feasibility studies are concurrently presented. The analyses include: transport, the agricultural and industrial parts of greenhouse gas emissions, the potential for increased exports as well as domestic job creation, and the total effects on health costs. Electricity market trade analyses and sensitivity analyses are also included. The paper thus presents technical energy system analyses of the total system with a multitude of interrelated technologies as opposed to just one technology or one category of effects. The final year of analysis is 2050, while two intermediate years are

also analysed, 2015 and 2030. The methodology includes hour by hour simulations leading to the design of flexible energy systems with the ability to balance electricity supply and demand and to exchange electricity production on the international electricity market. The paper describes the process, analyses and results of the IDA Climate Plan 2050 [24] from the Danish Society of Engineers (IDA) which was completed in August 2009. As a point of departure, the latest business-as-usual projection to 2030 from the Danish Energy Authority (DEA) has been used [25]. Utilizing the same methodology, a projection has been extended towards 2050 in the IDA Climate Plan 2050. The analyses build partly on the experience and analyses in the IDA Energy Plan 2030 from 2006 [22;26-28].

2. METHODOLOGY

The methodology for analysing technologies in the Climate Plan, and for assessing the technical and socio-economic consequences, can be divided into three parts. The data and technology input phase, the phase for adjusting energy systems technically and insuring flexibility, and finally the main technological and socio-economic results. In addition, fuel prices and CO_2-qouta prices are essential to the analyses. For more details on the methodology, results and sensitivity analyses please refer to Mathiesen et.al (2009) [24].

There are four overall goals in the project:

- To reduce the emission of greenhouse gases by 90per cent in 2050.
- To maintain Denmark's self-sufficiency with energy.
- To enlarge Denmark's position with regard to trade in the climate and energy sectors.
- To expand the economy and prosperity of Denmark.

The target of maintaining security of supply refers to the fact that Denmark, at present, is a net exporter of energy due to the production of oil and natural gas in the North Sea. However, the reserves are expected to last for only a few more decades. Consequently, Denmark will soon either have to start importing energy or develop domestic renewable energy alternatives. The targets of expanding the economy are related to past experiences with stabilising primary energy consumption and creating new industries.

2.1. The creative innovation process

The Danish Association of Engineers appointed 2006 as the “Energy year”, in which the organisation intended to make specific proposals to advocate an active energy policy in Denmark. The output here was the IDA Energy Plan 2030. In 2008, the process of updating and expanding the analyses was initiated as a part of the international project “Future Climate”, in which 13 engineering associations from Sweden, Norway, Germany, India, United Kingdom, Finland, USA, Japan, Australia, Ireland, Bulgaria and Denmark participated. The combined recommendations were presented in September 2009, and both the Danish and the other national documents and analyses were based on a common set of parameters.

The Climate Plan builds on the knowledge about technologies and their technological and economic effects on the overall energy system from the IDA Energy Plan 2006 [22;26-28]. In the process of developing the scenarios in the Climate Plan, the methodology applied to the design of a future renewable energy system included the combination of a creative phase involving the inputs from experts, a detailed analytical phase involving the technical and economic analyses of the overall system, and feed-back regarding each individual proposal. In a forward and back process, each proposal was formed in such a way that it combined the best

of the detailed expert knowledge with the ability of the proposal to fit cohesively into the overall system in terms of technical innovation, efficient energy supply and socio-economic feasibility. In addition, some of the proposals build on knowledge about the different technological components relating to the integration of intermittent renewable resources. Examples include: electric vehicles and fuel cell vehicles, district heating and individual heating systems, large-scale heat pumps, heat storages and electrolysers [5;6;18;29-31].

The work was divided into themes under which the following three types of seminars were held in 2006: First, a status and knowledge seminar; second, a future scenario seminar; and finally, a roadmap seminar. The process was organised into approximately 40 seminars and meetings with over 1,600 participants, resulting in a number of suggestions and proposals on how each theme could contribute to national targets. In 2009, the need for updates, amendments and adjustments had been identified through more than 10 workshops, seminars and conferences, as well as through sub analyses.

2.2. Fuel and CO_2-prices

Three fuel price levels are used, the middle level is based on the prices from the DEA corresponding to an oil price of $122/barrel. The high prices from the spring/summer of 2008 are used for a high price level of $132/barrel [32]. For the low price level, the low price assumptions which The DEA used in its projection from July 2008 at $60/barrel are used [33]. Calculations are also done with long-term CO_2 quota prices of, respectively, 229 DKK/ton (30€) and 458 DKK/ton (60€). The CO_2 quota price does not include all costs to the economy, such as e.g. floods, but is only an anticipated quota price. If these types of effects are included in the calculation, there will be an advantage for the energy systems in the Climate Plan.

The analyses of the effects of international electricity exchange have been done with a starting point in which electricity prices in a normal year are assumed and with fluctuating fuel and CO_2 quota prices. The net income is the combined calculation of import/export incomes including bottleneck incomes and various CO_2 and fuel costs. This net income is compared to not electricity trading with the surrounding countries.

2.3. Analysis Methodology

Technical energy system analyses and estimates of economic consequences of a 2030 energy system and a 2015 energy system have been done in which the necessary changes towards the long term goal in 2050 have been initiated. The proposed energy systems are called IDA 2015, IDA 2030 and IDA 2050.

IDA 2015 takes its starting point by incorporating technical changes that are technologically possible in the short term. The IDA 2050 energy system draws upon technologies which are expected to be developed in the future, such as better electric vehicles, fuel cells for CHP plants and electrolysers etc. If one or more of these technologies are not developed, there are other possibilities to utilize existing technologies so that the general conclusions remain intact. The IDA 2030 energy system represents a step in the direction of an IDA 2050 energy system. IDA 2030 and IDA 2050 will be carried out by technological measures which are estimated to be developed by the year 2020.

The Climate Plan is meant to be carried out over a period from now until 2050 by continuously replacing worn-out facilities when their lifetime runs out, and would therefore have been replaced anyway. The expenses are calculated as extra expenses through investing

in better facilities in relation to the reference energy system. There are, however, a few exceptions to this.

In the IDA 2050 energy system, significant structural and infrastructure changes are proposed in relation to the present. As the first energy plan in Denmark, a draft is done here of what the costs are for an energy system that is 100 per cent based on renewable energy. The results of the technical and economic analyses are, just as for IDA 2015 and IDA 2030, calculated by comparing IDA 2050 with the reference for 2050.

The technical energy system analyses have been done for the purpose of ensuring flexibility and balance between electricity production and consumption with regard to the system's fuel efficiency and its ability to ensure stability of the electrical network. A balance is identified between the intermittent renewable energy production, CHP production, and electricity consumption, including flexible electricity consumption from heat pumps, electric vehicles, etc. In addition, a corresponding balance is ensured between district heating consumption and heat production from solar heat facilities, industrial surplus heat, waste combined heat and power, centralised and decentralised combined heat and power, geothermic energy, boilers, heat pumps and electrical cartridges. The results of the analysis are, among other things, annual fuel consumption and CO_2 emissions which can be compared with a corresponding analysis of the reference.

The balance between consumption and production is ensured in a closed energy system in which electricity is not traded on the international electricity market, but only traded within Denmark. This ensures partly that an energy system is established where the domestic security of supply is intact and partly that Danish energy producers are not forced to export or to import at times when the market price is not favourable. Apart from these considerations, it is ensured that electricity and biomass for the energy system can be supplied with domestic resources. This ensures a more favourable position while trading in electricity and biomass with foreign countries than with dependency on imports or exports at certain times. It should be noted that the aim is not to avoid the international trade of electricity or biomass, just that it should be considered as a step in the overall analysis.

The socioeconomic costs are calculated as annual expenses in each of the years 2015, 2030 and 2050. The annual costs in the Climate Plan's energy systems are compared with the costs in the reference in the applicable years. The costs are allocated to fuel, operations and maintenance expenditures, and capital investment. A real interest rate in the economy of 3 per cent is used for the depreciation of facilities. Also, the marginal costs and effects on CO_2-emissions of each proposal have also been calculated in both the reference for 2030 energy system and IDA 2030.

2.4. The EnergyPLAN energy system analysis model

In all the energy systems, the analyses have been done by analysing the system hour by hour in the energy system analysis model EnergyPLAN, which has been used for technical system analyses as well as estimates of economic consequences [34]. The model is an input/output model that performs annual analyses in steps of one hour. Inputs are demands, capacities of the technologies included, demand distributions, and fluctuating renewable energy distributions. A number of technologies can be included enabling the reconstruction of all elements of an energy system and allowing the analyses of e.g. wind integration technologies, as well as the interrelation between the electricity and heat supply with high penetrations of CHP. The model makes it possible to use different regulation strategies putting emphasis on

heat and power supply, import/export, ancillary services, grid stability and excess electricity production. Outputs are energy balances, resulting annual productions, fuel consumption, and import/exports.

2.5. The reference energy system towards 2050

The calculations in the Climate Plan have been made by comparing the IDA scenarios with the sequence for a reference energy system. The latest business-as-usual projection to 2030 from the DEA has been used [25]. The DEAs projection contains a new forecast of the Danish energy consumption and production which takes into account the latest energy policy agreements. And using the same methodology, the projection has been extended towards 2050 for the IDA Climate Plan 2050 [24].

2.6. Input proposals to IDA's Climate Plan 2050

The contributions resulting from the process leading up to the analyses in the Climate Plan involved a long list of energy demand side management and efficiency measures within households, industry and transportation. These are combined with a wide range of improved energy conversion technologies and renewable energy sources, putting emphasis on energy efficiency, CO_2 reduction, and industrial development. All such proposals are described in relation to the reference energy system in 2015, 2030 and in 2050. Such descriptions involve technical consequences as well as investments, lifetime, and operation and maintenance costs.

2.7. Methodology for analysing health costs

External costs can be many things – they can involve including costs from environmental effects where the fuel has been extracted (e.g., a coal mine in South Africa) or can include health and environmental effects where the fuel is used. The costs included here are based on effects from the fuel conversion in Denmark, i.e., emissions from the energy system, and therefore do not include environmental and health costs from extraction and transport of the fuels to Denmark. Only health costs are included and not costs of environmental changes on agriculture, types of nature, buildings etc. It does, however, include the health effects of Danish emissions to neighbouring countries.

A range of studies exist concerning pricing of health effects as a consequence of discharging various contaminants [35;36]. Perhaps the best known is ExternE (www.externe.info), an EU project started in 1990'ties which is constantly updated [37]. The National Environmental Research Institute, Denmark (NERI), has also updated these numbers several times according to Danish conditions (www.dmu.dk) [38] including a more advanced air pollution model than was originally used in ExternE. This version is used by, among others, the DEA in evaluating the socioeconomic value of projects. The ExternE models concerning air pollution have been improved at the Centre for Energy, Environment and Health (CEEH) (www.ceeh.dk), which is a cross-disciplinary centre which utilizes, among other aspects, a smaller geographic resolution [39]. This means that the average concentration of air pollution contaminants to which the population is exposed can be calculated more precisely and therefore a better estimate can be given for the associated costs. These costs are based on enumerated lost work days, hospital admissions, health damage, deaths, etc. Six different emissions are included: SO_2, NO_x, CO, particulates (PM2.5), mercury, and lead.

The socioeconomic costs as a result of these discharges are quantified separately on the basis of fuel consumption and conversion technology. The costs in the IDA scenarios are compared with the costs of the emissions in the reference energy systems. The estimation of emissions

takes a starting point in NERI's latest estimate of emissions allocated by fuels and technologies.

2.8. Methodology for assessing commercial potential and job creation

For the analysis of commercial potential, a starting point is taken in previous experiences with building up new types of industries within the energy and building sector in Denmark. This is compared with the investments in renewable energy and the investments in energy conservation measures in the Climate Clan compared with the reference.

The employment effect likewise takes a starting point in the above-mentioned differences in the Climate Clan and the reference. Previous estimates of import share with various cost types are used here, as well as an estimate of the effect on employment from domestic investments.

3. RESULTS

In this section the results from the process of identifying inputs to the Climate Plan and the following analyses are presented. The results are divided into conclusions on primary energy demand, CO_2-emissions, socio-economics, health costs, commercial potential and job creation.

3.1. Main results of the data gathering process

In the process of up-dating and gathering new information about the technological proposals, the three target years are taken into consideration. For 2015 the technologies proposed have a rather short term timeframe to be implemented. For 2015 only well developed technologies are implemented. It should be noted that some of the technologies proposed in 2015 should be implemented over the period from now until 2020, since these are larger infrastructural changes. All proposals, however, are analysed as though they were fully implemented in 2015. In 2030, many aspects of the transport system are also changed, the district heating system is heavily expanded and power plant and combined heat and power plants are based on more efficient technologies. In addition, more of the well developed as well as new renewable energy technologies are implemented. In general, a large proportion of fossil fuel usage is replaced by electricity demand, particularly in the transport sector, where more electric vehicles are used as well as more electric trains.

Table 1, Renewable energy used for electricity production in the reference years and in the proposed energy systems.

	2008	2015	2030	2050	IDA 2015	IDA 2030	IDA 2050
Wind turbines (%)	19	28	28	27	48	67	63
- percentage onshore (%)	16	18	16	13	28	36	25
- percentage offshore (%)	3	10	12	14	20	31	38
Wave power (%)	0	0	0	0	0	4	5
Photovoltaic (%)	0	0	0	0	0	3	9
Biomass (%)	11	17	32	26	19	11	22
Synthetic fuels (%)	0	0	0	0	0	0	1
Of total electricity production (%)	30	45	60	53	67	85	100
Total production (TWh)	36.5	36.7	41.8	51.5	32.1	34.8	50.4

In 2050 the IDA Climate Plan proposes a 100 per cent renewable energy system by implementing more renewable energy technologies, reducing final energy demand, and by making further infrastructural improvements within the transport sector.

In Table 1, the increase in renewable energy production from different sources for the three target years is listed. In Table 2, the same results on the renewable energy percentages are presented for the heating of individual houses as well as in overall district heating supply.

Table 2, Renewable energy in the heat supply.

Individual heating systems	2008	2015	2030	2050	IDA 2015	IDA 2030	IDA 2050
Solar thermal (%)	1	1	3	3	4	23	23
Heat pumps (%)	4	9	14	17	35	65	67
Biomass (%)	47	46	50	48	43	10	10
Of total demand (%)	51	56	67	68	83	98	100
Total demand in individual heating systems (TWH)	22.9	22.0	19.5	16.3	14.7	9.3	8.8

District heating production	2008	2015	2030	2050	IDA 2015	IDA 2030	IDA 2050
Solar thermal (%)	0	0	0	0	1	8	8
Large-scale heat pumps (%)	1	0	0	0	10	24	25
Electric boilers (%)	0	0	0	0	2	1	1
Biomass (%)	24	26	35	35	24	39	66
Synthetic fuels (%)	0	0	0	0	0	0	0
Of district heating production (%)	25	26	35	35	37	71	100
Total production, incl. district cooling and for biogas production (TWh)	36.70	36.10	35.52	35.53	38.04	40.63	40.79
Total production to connected houses and industry	35.87	35.28	34.06	34.06	37.49	37.72	37.28
Total end heat demand (an consumer), excl. grid losses	26.90	27.87	26.91	26.91	29.62	29.80	29.45
Solar thermal of end demand (%)	0	0	1	1	2	11	11

In addition to these increases in the renewable energy share, the following have been implemented:

- Graduel implementation of fuel cell CHP and power plants
- Higher efficiency waste incineration plants
- Large-scale solar thermal and geothermal plants for district heating
- 50 per cent reductions in the household electricity and heat demand
- 75 per cent lower heat demands in new buildings
- Reduction of electricity consumption in industry of 45 per cent, fuel savings of 33 per cent and replacement of fossil fuels with large-scale heat pumps and biomass.
- Transfer of increases in transport demand to trains, and management of growth by road pricing
- Extensive use of battery electric vehicles and hybrid battery electric vehicles.
- Heavy expansions of railroads.
- Expansion of bicycle usage
- More goods via freight trains and ships.

- More efficient ships
- More efficient aviation based on fuels derived from biomass.

For the purpose of estimating the level of supply security, the biomass resources are identified. Most scenarios and prognoses for use of biomass have first and foremost had a focus on use of biomass for energy purposes, including electricity, heat, and propellants for transport. However, a need for production of materials must also be covered if these no longer can be produced by fossil fuels. In keeping with this, a focus on integrated use of biomass has appeared. In Table 3**Error! Reference source not found.** a range of estimates of the Danish biomass resources has been displayed. In addition, the consumption for 2006 has been shown, as well as imports and Danish-produced biomass.

Table 3, Biomass resources for energy purposes in Denmark: Consumption 2006 and various scenarios. Numbers have been expressed as PJ, understood as the calorific value of the various forms of biomass.

PJ	Consumption of Danish resources	Imports	DEA potential [40]	Potential in IDA Energy Plan 2030 [26;28]	IDA Climate Plan 2050 [24]
Straw	18	0	55	55	30
Wood	38	16	40	40	50
Biomass to biogas	4	0	40	40	40
Slurry fibre fraction	-	-	0	108	5
Energy crops	-	-	0	144	52
Biodegradable waste	30	0	30	30	30
Algae	-	-	-	-	100
Total	90	16	Approx. 165	417	307

The differences in the various potentials for biomass in Denmark have to do with evaluating yields, size of area, quantity of straw, crop types, etc. Algae have been brought into the scenario for the Climate Plan. As energy crops, algae are associated with significant uncertainties because the environmental effects of this technology are uncertain. Energy crops such as maize or beets can be cultivated without affecting agricultural production. This is partially due to the production of such by-products as liquid biofuels, solid fuels, and fodder that must not be cultivated at other places, and partially with the help of bringing in fallow fields. Under the assumption that the balance in current agricultural production is maintained, approximately 20 per cent (500,000 hectares) of the Danish agricultural area can be converted to the cultivation of energy crops, for example maize. By that means, the Danish biomass resource will be increased considerably. In connection with the completion of IDA Energy Plan 2030, it was estimated that if maize is used for combined production of liquid biofuels, solid fuels, and fodder, the net area demand for an energy production of 144 PJ is approximately 330,000 hectares or around 15 per cent of the agricultural area.

In the Climate Plan, 100 PJ from algae is displayed, cf. more information in [24]. This is, however, associated with the use of a large area. Hence a final position has not been taken in the Climate Plan on the balance between the use of biomass from algae and that from energy crops. In IDA's Climate Plan 2050, biomass is used in CHP plants, in transport in the form of IBUS facilities, as well as in waste incineration and industry.

It is not realistic to use the entire biogas potential by 2030. It is assessed that it is possible to achieve a usage of 75 per cent of the biogas potential, corresponding to 32 PJ. In IDA 2050, it is assumed that the entire potential of 40 PJ is used.

A full description of the measures is described in Mathiesen et.al (2009) [24].

3.2. Introducing flexibility while maintaining fuel efficient renewable energy systems

With a starting point in the three reference energy systems, the energy system in IDA 2015, IDA 2030, and IDA 2050 the sum of the above-mentioned initiatives can be analysed. At first glance (step one) these initiatives result in an energy system with large imbalances between consumption and production, which are expressed in the form of a significant electricity surplus which the energy system has been forced to export. In addition, this results in a decreased opportunity to earn money through trading on the international electricity market. Hence a range of technical improvements of the combined system have been done for the purpose of creating greater flexibility, while, at the same time, ensuring a fuel efficient energy system. In IDA 2015, the adjustments are made as the second step by introducing thermal heat storages at CHP plants, allowing them to adjust electricity production to periods with no or low wind power production. As the next step, large-scale heat pumps are installed at CHP plants, allowing district heat supplied by boilers to be replaced while also using electricity at times with high wind power production. In IDA 2030, further steps are needed. Flexible demands are introduced for 15 per cent of demand in industry and households, smart charging of battery electric vehicles is introduced, and the fuel cell CHP plants installed in IDA 2030 are used to increase flexibility even further**Error! Reference source not found.**. Such plants can potentially be regulated very quickly from nil to full capacity, much faster than the current steam turbines. In the IDA 2050 energy system, electrolysers and synthetic fuel storage facilities are introduced at CHP plants, enabling the system to be based 100 per cent on renewable energy and replacing parts of the biomass consumption at CHP plants. The synthetic fuels from electrolysers are implemented as hydrogen, but could potentially be other fuels such as DME, methanol, methane etc. In Fig. 1 the effects of the steps in the IDA 2030 energy system are illustrated. Similar effects are present in the process of making the energy systems for IDA 2015 and 2050 more flexible.

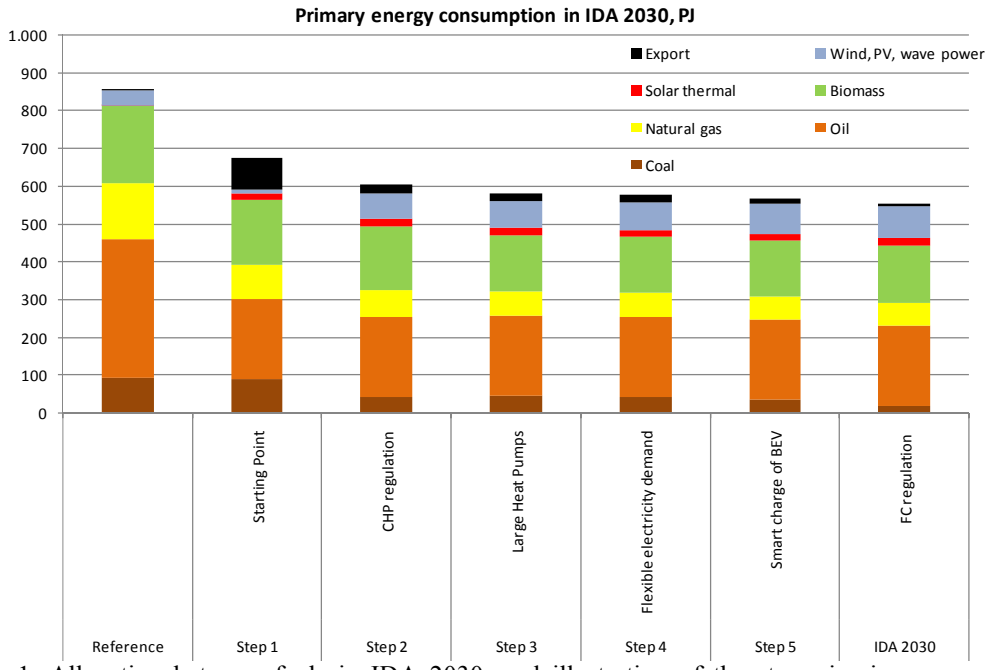

Fig. 1, Allocation between fuels in IDA 2030, and illustration of the step-wise improvements through technical adjustments of the system.

3.3. 100 per cent renewable energy and large reductions in fuel consumption

The current primary energy consumption in Denmark is approx. 800 PJ including transport and industry. The DEA expects the energy consumption to decline marginally towards 2015, because of already existing or planned energy savings followed by an expected increase to

approx. 950 PJ in 2050. In the Climate Plan, the suggested changes decrease the primary energy consumption to 707 PJ in 2015, 556 PJ in 2030 and 442 PJ in 2050. Simultaneously while reducing demand, renewable energy sources are implemented. This increases the percentage of renewable energy from 22 in the 2015 reference to 30 in IDA 2015, and from 25-29 per cent in the reference in 2030 and 2050 to 47 in IDA 2030 and 100 per cent in IDA 2050. In Fig. 2 the resulting primary energy consumption is presented.

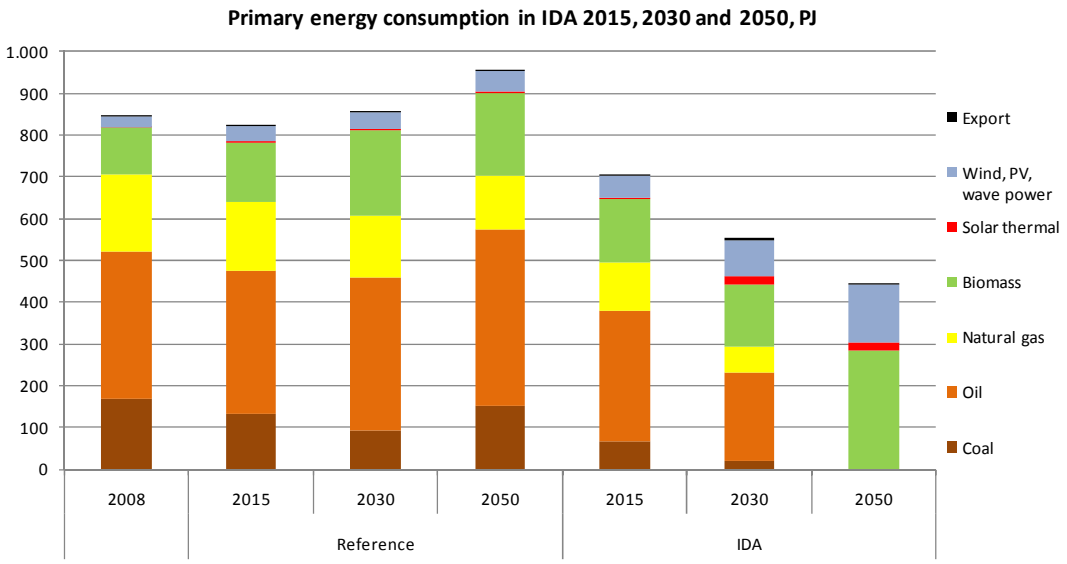

Fig. 2, Primary energy consumption in the reference and IDA scenarios. The reference energy systems are based partly on business-as-usual projections from the Danish Energy Authority and a projection performed in the Climate Plan for the years from 2030 to 2050.

In both IDA 2015 and IDA 2030 there are sufficient domestic biomass resources. Meanwhile, there are challenges in the IDA 2050 energy system, where 284 PJ of biomass is used. This can potentially be supplied with domestic resources, but conversely it will not leave many resources for any material goods production. It is a challenge for the future regarding whether more of the fuel consumption in industry and aviation can be changed to direct or indirect electricity production, or whether further end demand savings can be introduced.

A 100 per cent renewable energy system has been designed which potentially can be maintained by domestic biomass resources. It must be emphasised that there is no objective in the Climate Plan to not conduct international trade with biomass. It does, however, present the opportunity for Denmark to avoid a future dependence on foreign biomass as it would experience with oil, natural gas and coal in the reference, due to the anticipated exhaustion of oil and natural gas resources in the North Sea within the next decade or so. In Fig. 3, the IDA 2050 resulting energy system is represented with a sankey diagram.

In IDA 2050, the energy system including transport can also be supplied with the biomass potential purely from a quantity point of view. However, the surplus biomass resources beyond this are small, and thus there are not sufficient resources for the production of materials, for example. In IDA 2050 a large portion is devoted partly to international aviation, partly to industry, and partly to waste incineration plants. It has not been possible to investigate all technological possibilities within these sectors in the Climate Plan. In the future, it is recommended to investigate:

100% renewable energy. Primary energy supply, total: 122,86 terawatt hour (TWh)

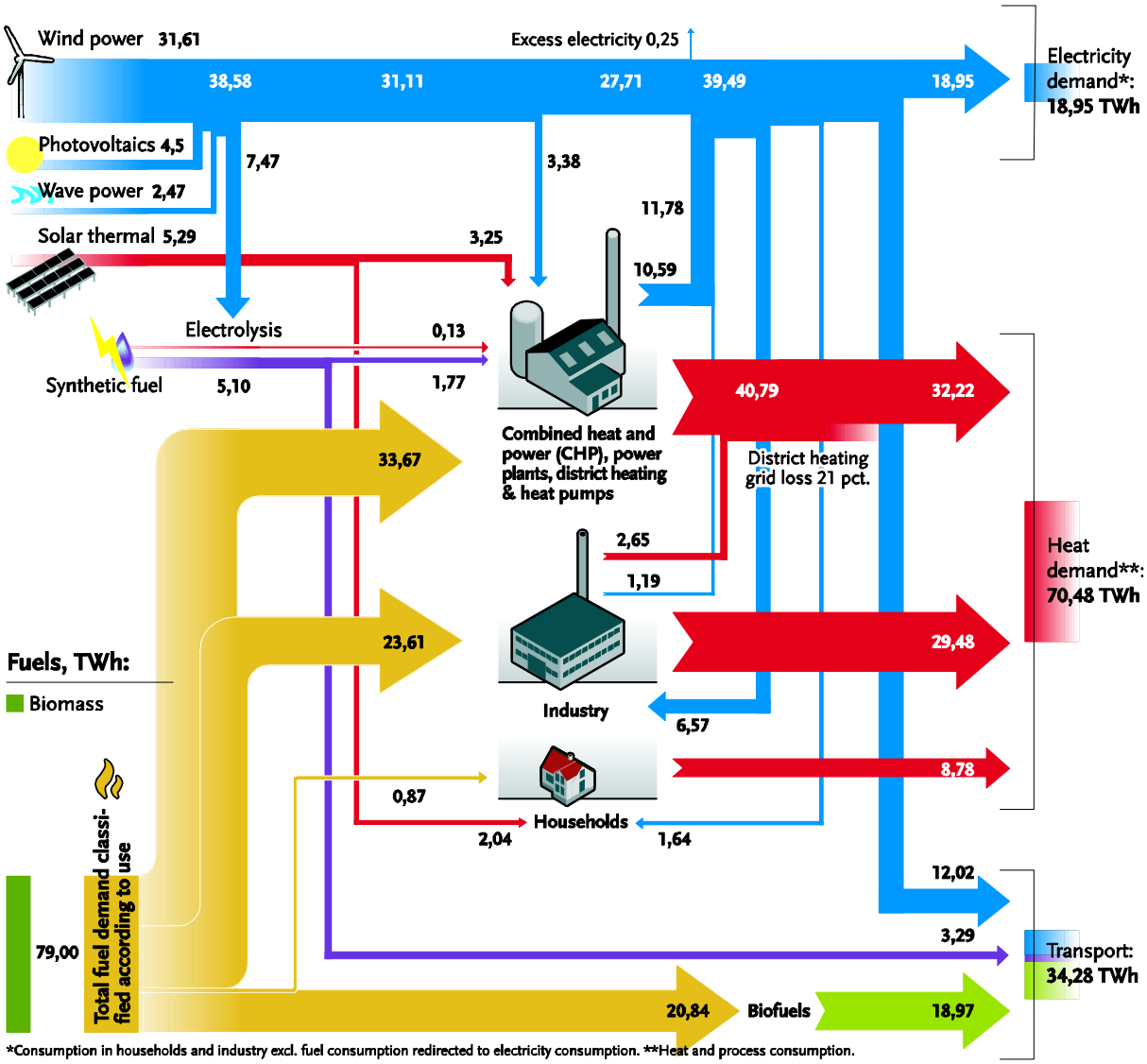

Fig. 3, Sankey diagram of the resulting energy system for 2050.

- Whether synthetic fuels for aviation can be developed that can replace biomass-based fuels for aviation efficiently.
- Whether a portion of the international air transport can be covered by international high speed trains.
- Whether aircrafts can be made even more efficient.
- Whether the transport demand for international aviation can be reduced.
- Whether even more fuel consumption for industrial processes can be shifted to electricity consumption than displayed here.
- Whether more savings can be made within industry.
- Whether a larger quantity of waste can be recycled instead of being burned.

- Whether a portion of the waste resource can be converted to gaseous biofuels for example, where parts can be stored and parts can be used more efficiently than in waste incineration facilities.
- Whether waste incineration can be made more flexible with other techniques, without the waste simply being burned off in a boiler.
- Whether waste incineration can be done more efficiently by raising the electricity efficiency.

3.4. Large reductions in greenhouse gas emissions

The objective is reductions in the emission of greenhouse gases of 90 per cent in 2050 in relation to 2000. The energy system constitutes only a part of the emission of greenhouse gases. This part will be reduced to 34 mill. ton CO_2 in 2015, 19 mill. ton CO_2 in 2030, and is completely removed in 2050 by the changes described above. Beyond this, reductions in the emission from industrial processes and from agriculture are proposed, and the extra contribution from aircraft is taken into account, because of emissions in high altitudes. All in all, the emissions in 2050 can be reduced to 7.2 per cent of the emissions in 2000. If the aircraft contribution is included, the reduction is 10.2 per cent. In Fig. 4 the reductions in the plan are illustrated.

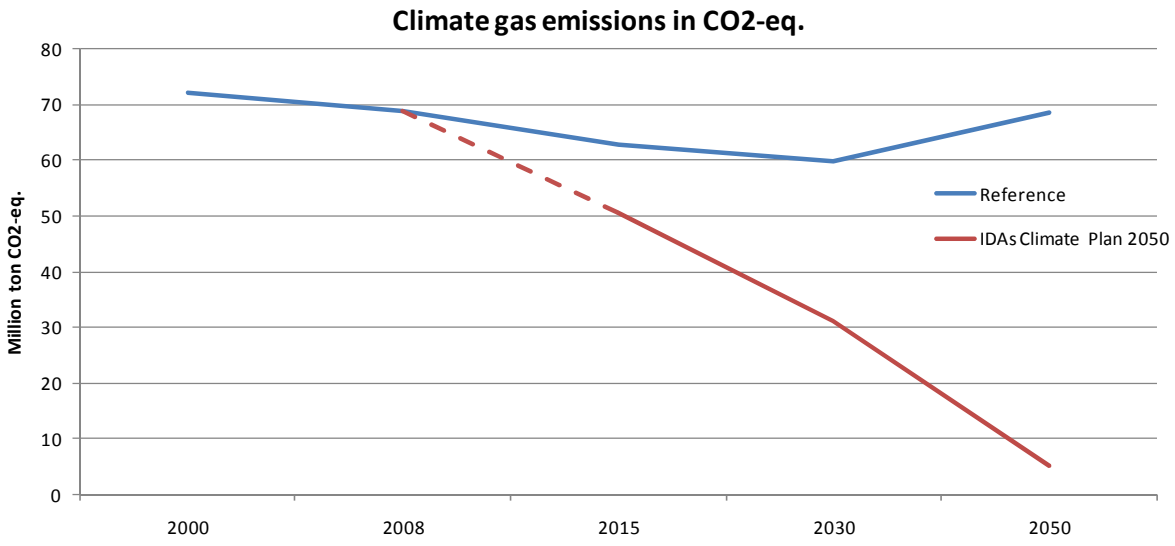

Fig. 4, Emission of Greenhouse Gases in the reference and the Climate Plan.

3.5. Better socio-economic solutions with more renewable energy

The general picture is that Denmark will achieve a significantly better economy with both IDA 2015 and IDA 2030 than with the reference energy systems. In 2015 and 2030 the difference with the middle fuel and low CO_2 price assumptions are respectively 9 and 20 billion DKK/year, as illustrated in Fig. 5. In IDA 2015 it is important, however, to note that a part of the measures are undertaken in the period 2010 to 2020. For the 2030 energy system, the marginal economic value as well as the marginal effect on the CO2-emissions has also been analysed, cf. Mathiesen et.al (2009) [24].

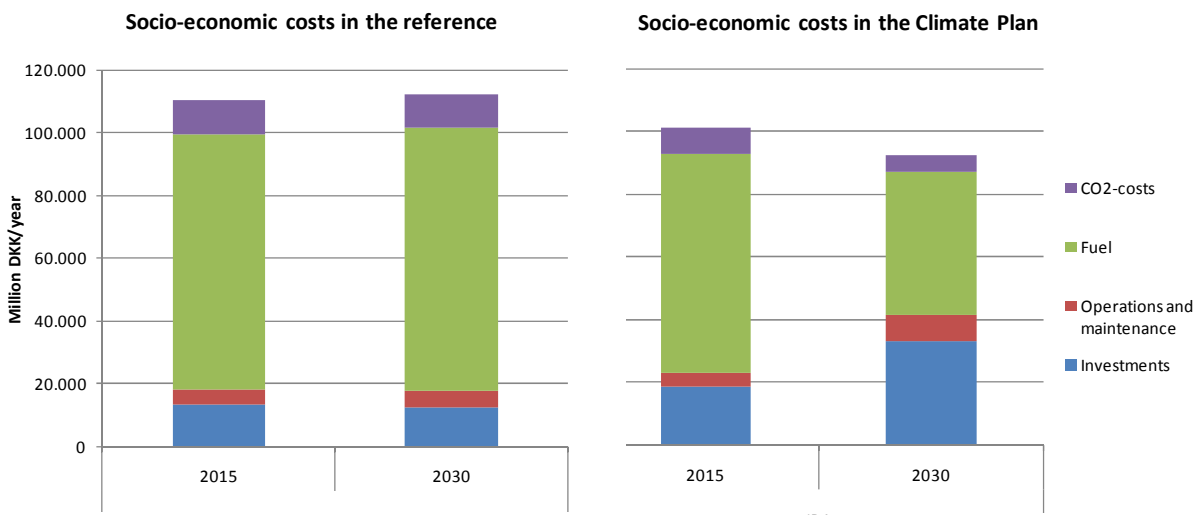

Fig. 5, Costs to the economy in 2015 and 2030

In addition, a more robust situation is reached, while the combined costs for energy are less sensitive to fluctuations in oil prices and CO_2 costs. There will be a gain even if fuel prices are half as high as the DEA currently recommends. It is worth noting that annually, between 50 and 95 billion DKK/year today and going forwards to 2030 will be spent on fuels, depending on the fuel prices. It is proposed in the Climate Plan that these expenditures be reduced to between 29 and 51 billion DKK/year, again depending on the fuel prices. Two advantages can be obtained. In part, IDA 2015 and IDA 2030 are less expensive than the reference energy systems, and in part, it involves a system significantly less sensitive to fluctuations in the fuel prices. In the future, one must expect that the world will continue to experience fluctuating prices, with neither constantly high nor constantly low oil prices.

IDA 2050 is based on 100 per cent renewable energy. The estimate of the costs to the economy shall be seen as a first attempt to estimate the costs to the economy in such a system. Such estimates, however, are associated with significant uncertainties. In 2050 there is a wide range of measures, among others electricity and heat savings, that are altered only marginally in relation to the measures in IDA 2030. The most important changes are that the share of renewable energy is raised significantly in the electrical system, the power stations are more efficient, synthetic fuels from electrolysis have replaced a part of the biomass and the transport sector is to a greater degree converted to track-borne forms of transport and electrical vehicles. It must be emphasised that the results are dependent on the fuel price assumptions, as well as the significant structural societal changes that are proposed in IDA 2050. IDA 2050 is robust regarding larger changes in the biomass prices than analysed here. The results are that there are potential savings of over 25 billion DKK/year in the middle fuel price scenario, as illustrated in Fig. 6.

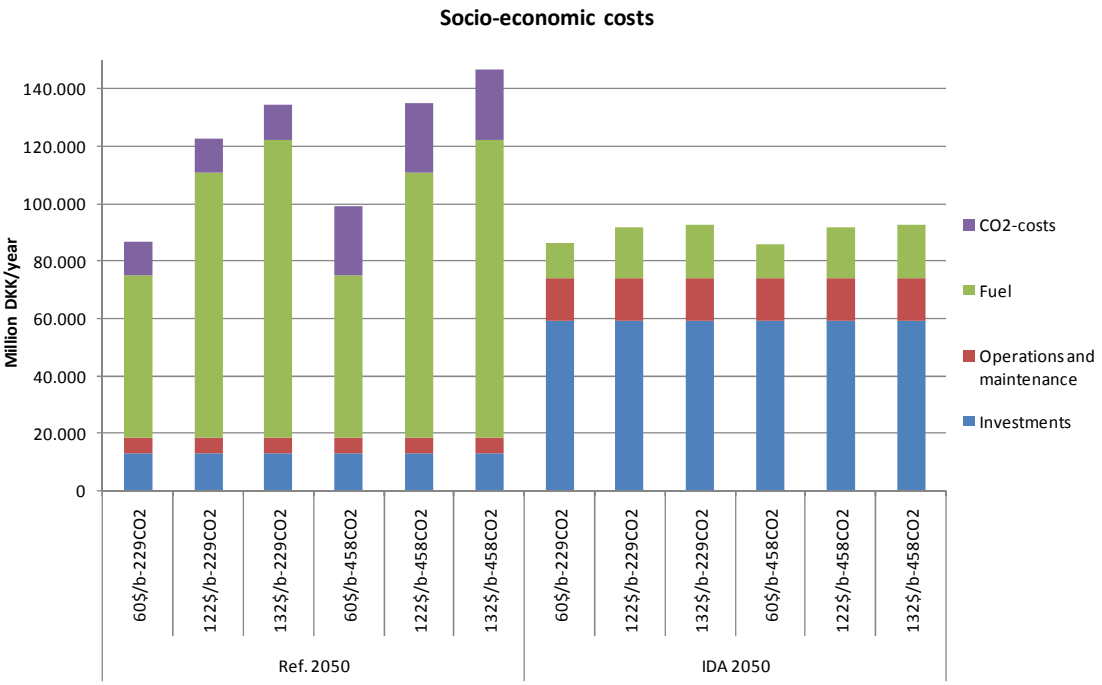

Fig. 6, Costs to the economy in 2050 at different fuel and CO_2 prices

Analyses of the consequences of international electricity exchange on the Nord Pool have also been conducted. The above-mentioned estimation of the costs to the economy are in a closed system without international electricity trading. In situations with low fuel prices and low CO_2 quota prices, income is primarily through electricity exports, while in the case of high fuel prices income is primarily through imports. Therefore, there is also a difference in the earnings from electricity trading in the two systems. The energy systems proposed provide higher income, primarily because of more efficient power stations combined with available capacity when the consumption is covered by wind turbines, etc. This will, however, result in larger CO_2 emissions in Denmark and increased coal or biomass consumption. All in all, it involves a difference however which is of less significance in comparison with the difference in the annual costs of the system itself presented above, which amounts to several billion DKK/year to the advantage of IDA 2015 and IDA 2030. In the references for both 2015 and 2030, as well as in IDA 2015 and IDA 2030, an increase in the transmission capacity to other countries from 2.500 MW to 5.000 MW only provides an opportunity for marginal extra income, which does not at all match costs associated with this extra capacity. The conclusions of the electricity exchange analyses of the 2050 energy systems are estimated to be in keeping with the above results. It must be emphasised that the analyses of a closed energy system without trading are not an expression that international trade of electricity should be avoided in the future. This is only done in order to ensure that the energy systems in the Climate Plan are not dependent on this or dependent on shutting down wind turbines, etc., in certain situations. The energy systems in the Climate Plan are in a position to avoid this.

Any possible changes in assumptions regarding international electricity trade are not critical for the comparison. The large difference is summed up by the Climate Plan including large investments, while the reference has large fuel costs. Hence the comparison is especially sensitive partly to changes in the fuel prices and partly to changes in interest rate and investment requirements. Analyses have been done at three fuel levels and the two CO_2 quota price levels which do not change the general picture that the Climate Plan has lower costs than the reference. Nor are the results changed by an increase of the investment levels by 50

per cent, although the earnings become lower. The same is the case if the real interest rate is at 6 per cent. It must be pointed out, however, that this applies to the combined package. With an altered interest rate or scope of investment, several of the individual measures will get a negative economic result.

3.6. Health costs

The health costs have been estimated on the basis of six different emissions: SO_2, NO_x, CO, particulates (PM2.5), mercury, and lead. In IDA's Climate Plan 2050, the highest reductions are in the emissions of NO_x CO, and small particulates. There are also reductions in the emissions of SO_2, mercury, and lead. The reduced emissions are primarily because of much less coal used in the power plants, less diesel and petrol in the transport sector, reduced demand for oil in industry, and a reduced demand for wood in individual household heating. On the other hand, the emissions increase marginally because of more straw, wood, biogas, etc.

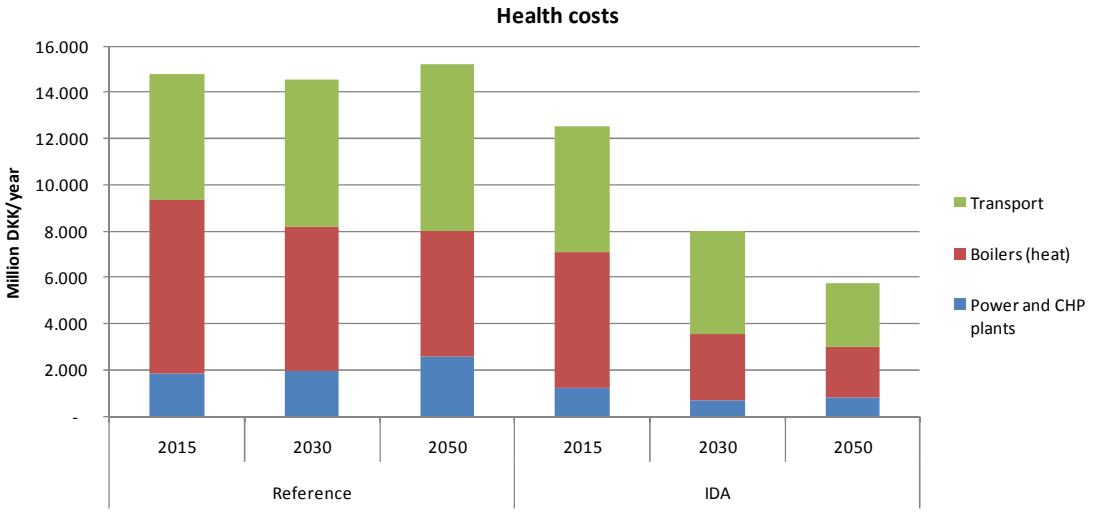

Fig. 7, Combined health costs from the energy systems divided by sector.

The costs are based on enumerated lost work days, hospital admissions, health damage, deaths, etc. The combined health costs for the reference energy systems for 2015, 2030, and 2050 are approximately 14 to 15 billion DKK/year. The combined health costs estimated here fit well with other studies. In IDA 2015, these costs have been reduced to approximately 13 billion DKK. In IDA 2030 and 2050, the costs have been reduced to, respectively, about 8 and 6 billion DKK. The health costs included are based exclusively on the six emissions and do not include environmental costs due to damage to nature and animal life, nor costs from extraction of fuels and materials abroad, e.g., from a coal mine in South Africa. Hence it can be regarded as a rather conservative estimation. If the socioeconomic environmental and health costs due to the CO_2 emissions on top of the six emissions analysed here are included, a conservative estimate shows that the above-mentioned savings are approximately twice as large. The savings in the health costs are approx. 2 billion DKK in 2015, approx. 7 billion DKK in 2030 and approx. 10 billion DKK in 2050. In Fig. 7, the health costs have been estimated and are distributed by sector.

3.7. Commercial potential

A systematic implementation of the technologies that are included in the Climate Plan will include significant opportunities to increase exports. These potentials are evaluated with a starting point in the current and historic export of energy technologies. It is estimated that the Climate Plan can create a potential for exports of energy technology that climbs from the

present approximately 64 billion DKK in 2008 to approx. 200 billion DKK/year going forward to 2030. It must be emphasised that this type of quantification is associated with significant uncertainties and must be considered an estimate. However, the rough estimate provides a good overview of the technologies where the Climate Plan can potentially contribute to creating a trend. It must also be emphasised that these potential earnings come on top of the earnings that are shown through the changed operation and structure in the energy system itself. The results are illustrated in Fig. 8.

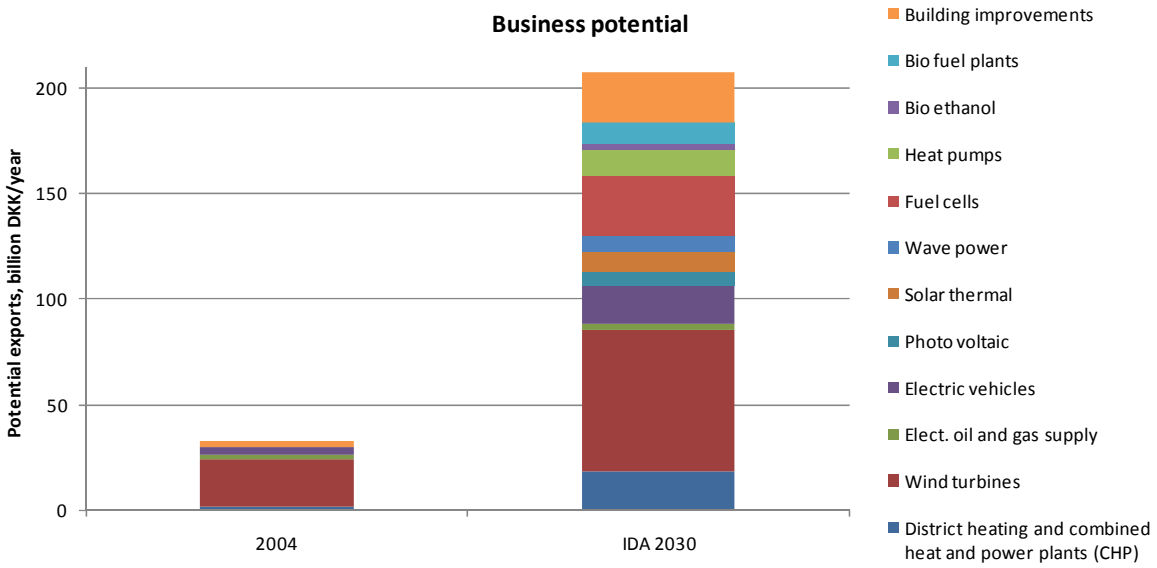

Fig. 8, Annual commercial business potentials of the Climate Plan.

3.8. Employment Effects

The starting point for the estimation of the employment effect is the division in annual costs for Climate Plan compared with that in the reference. The difference in the costs can be broken down into investments and operations. Implementation of Climate Plan 2050 includes a shift from significant costs devoted to fuel to expenditures for investments. Such changes will include higher Danish employment at the same time as an improvement in international balance of payment. This effect is increased further if the plan is implemented in a manner so that the above-mentioned commercial potentials in the form of increased exports are realised. In the Climate Plan, expenditures for fuels are reduced while they are increased for operations and maintenance. In addition, an extra investment just below 1 trillion DKK is made in the Climate Plan compared to the reference, spread out over the period going forward to 2050. For the share that is left, after removing the import share, two jobs continue to be created for each million DKK spent. This includes derived jobs in the finance and service sector. It should be emphasised that such estimates are subject to uncertainties. The extra employment in Denmark through implementation of the Climate Plan compared with the reference has been estimated with the method and assumptions to be about 30-40,000 jobs. Jobs will be lost in the handling of fossil fuels, but jobs will be created through investments in energy technology. In the long term, employment will settle down, in step with the completion of investments leading to a 100 per cent renewable energy system, to about 15,000 extra jobs in relation to the reference for 2050. In practice, this will probably spread out over a period of years. In this context, it is important to place the large employment effort as early as possible in the period for two primary reasons. The first reason is that the labour force as a share of the total population is falling during the entire period going forward to about 2040; therefore, the largest labour capacity to undertake a change in the energy system is in the beginning of the examined period. The other reason is that the Danish North Sea resources run out during this period. It is therefore important to develop such energy systems and changes as early as

possible. Also, the potential increase in the export of energy technology can replace the oil and natural gas exports expected to disappear entirely in the course of 10-20 years.

The above-mentioned effects on employment do not include job creation as a result of increased exports of energy technology. With an assumption of a 50 per cent import share, an annual export of 200 billion DKr will generate on the order of up to 200,000 total jobs, depending on where the exports would have been without the Climate Plan and on the extent of unemployment and the extent to which these persons could be employed in other export trades. In that connection, notice is directed to the fact that everything else being equal, a share of Danish labour will be made available in step with the conclusion of oil and gas extraction in the North Sea.

4. CONCLUSIONS

In IDA's Climate Plan 2050, an energy system is designed which is based on 100 per cent renewable energy for Denmark. The IDA 2015 and IDA 2030 energy systems represent steps on the way towards this goal. The result is that a 100 per cent renewable energy system is possible, but the balance between large consumption of biomass and large amounts of electricity for direct use, or for production of synthetic fuels, is a challenge. An estimate is presented here for this balance. In combination with changes in the agricultural sector, and including the extra contribution from aviation, the emission of greenhouse gases can be reduced to 10.2 per cent in 2050 compared to 2000 levels. Just the change from a conventional energy system to a renewable energy system provides large socio-economic savings from lower expenses for fuel by making investments in savings, more efficient technologies and renewable energy. On top of this, there is a benefit for the health of the population, which can increase the socio-economic savings. If the changes are implemented early in the period, there is a potential for large exports and related jobs. In all cases, the changes will increase the amount of jobs, even if the commercial potential for increased exports is not met.

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