Energy System Analysis of 100 Per cent Renewable Energy Systems

Lund, Henrik; Mathiesen, Brian Vad

Published in:
Proceedings of the 4th Dubrovnik Conference on Sustainable Development of Energy, Water and Environmental Systems

Publication date:
2007

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

Energy System Analysis of 100 Per cent Renewable Energy Systems

The Case of Denmark year 2030 and 2050

H. Lund*
Department of Development and Planning
Aalborg University, Aalborg, Denmark
e–mail: lund@plan.aau.dk

B. V. Mathiesen
Department of Development and Planning
Aalborg University, Aalborg, Denmark
e–mail: bvm@plan.aau.dk

ABSTRACT

This paper presents the methodology and results of the overall energy system analysis of a 100 per cent renewable energy system. The input for the systems is the result of a project of the Danish Association of Engineers, in which 1600 participants during more than 40 seminars discussed and designed a model for the future energy system of Denmark, putting emphasis on energy efficiency, CO2 reduction, and industrial development.

The energy system analysis methodology includes hour by hour computer simulations leading to the design of flexible energy systems with the ability to balance the electricity supply and demand and to exchange electricity productions on the international electricity markets.

The results are detailed system designs and energy balances for two energy target years: year 2050 with 100 per cent renewable energy from biomass and combinations of wind, wave and solar power; and year 2030 with 50 per cent renewable energy, emphasising the first important steps on the way. For the first step until 2030, the results include detailed socio-economic feasibility studies, electricity market trade calculations, and sensitivity analyses.

The conclusion is that a 100 per cent renewable energy supply based on domestic resources is physically possible, and that the first step toward 2030 is feasible to Danish society. However, Denmark will have to consider to which degree the country shall rely mostly on biomass resources, which will involve the reorganisation of the present use of farming areas, or mostly on wind power, which will involve a large share of hydrogen or similar energy carriers leading to certain inefficiencies in the system design.

1. INTRODUCTION

In a recent report from 2007, the United Nations' International Panel of Climate Change, IPCC, emphasises the many indicators on climate change and recommends that the world society responds to the serious problems. In the US, the European Union and China, policies have been formulated with the objective of decreasing CO2 emissions. And in many nations around the world, policies to raise the share of renewable energy are being initiated as part of the global response to climate change[1-10]. In March 2007, the European Union defined a

* Corresponding author

target of 20 per cent renewable energy for year 2020. In Denmark, a target of 30 per cent renewable energy for year 2025 has just been proposed by the Danish Government.

In Denmark, on the one hand, CO2 emissions per capita have for many years been among the highest in the world, but, on the other hand, an active energy policy has already led to remarkable results in the decrease of emissions [11]. For a period of 35 years, Denmark has managed to stabilise the primary energy supply, which is the same today as in was before the first oil crises in the early 70s. Furthermore, the share of oil is much smaller today. 20 per cent of the electricity is supplied by wind power and 15 per cent of the primary energy supply is renewable energy including biomass and waste incineration. Moreover, savings and efficiency measures have constituted an important part of the policy leading to a situation today in which 50 per cent of the electricity is produced by CHP (Combined Heat and Power).

In his opening speech to the Danish Parliament in October 2006, the Prime Minister announced the long-term target of Denmark: 100 per cent independency of fossil fuels and nuclear power. A few months later, the Danish Association of Engineers (IDA) put forward a proposal on how and when to achieve such targets. This proposal was the result of the "Energy Year 2006", in which 1600 participants during more than 40 seminars discussed and designed a model for the future energy system of Denmark, putting emphasis on energy efficiency, CO2 reduction, and industrial development. The proposal was presented as the IDA Energy Plan 2030 (See figure 1).

Figure 1. The Danish association of Engineers, IDA Energy Plan 2030 discussion

The design of 100 per cent renewable energy systems involve at least three major technological changes [12]: energy savings on the demand side [13;14], efficiency improvements in the energy production [15;16], and the replacement of fossil fuels by various sources of renewable energy [17;18]. Consequently, large-scale renewable energy implementation plans must include strategies for integrating renewable sources in coherent energy systems influenced by energy savings and efficiency measures [19-21].

The design of 100 per cent renewable energy systems has to meet especially two major challenges. One challenge is to integrate a high share of intermittent resources into the energy system, especially the electricity supply [22-29]. The other is to include the transportation sector in the strategies [30].

This paper presents the methodology and results of the overall energy system analysis of a 100 per cent renewable energy system. The methodology includes hour by hour computer simulations leading to the design of flexible energy systems with the ability to balance the electricity supply and demand and to exchange electricity productions on the international electricity markets.

The results are detailed system designs and energy balances for two energy target years: year 2050 with 100 per cent renewable energy from biomass and combinations of wind, wave and solar power; and year 2030 with 50 per cent renewable energy, emphasising the first important steps on the way. For the first step until 2030, the results include detailed socio-economic feasibility studies, electricity market trade calculations, and sensitivity analyses.

2. METHODOLOGY

The methodology of designing the proposal for a future sustainable energy system in Denmark was a combination of a creative phase involving the inputs of a number of experts and a detailed analytical phase involving the technical and economic analysis of the overall system and giving feed-back on each individual proposal. In a forward and back process, each proposal was formed so that it combined the best of the detailed expert knowledge with the ability of the proposal to fit well into the overall system, both in terms of technical innovation, efficient energy supply and socio-economic feasibility.

2.1 The creative innovation process of IDA Energy Year 2006

First, the Danish Association of Engineers appointed 2006 as the “Energy year” in which the organisation aimed at making specific proposals to advocate an active energy policy in Denmark.

Three targets were formulated for the future Danish energy system year 2030:

- To maintain security of energy supply
- To cut CO2 emissions by 50 per cent by year 2030 compared to the 1990 level
- To create employment and to raise export in the energy industry by a factor 4

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.

Based on such targets, the work was divided into 7 themes under which the following three types of seminars was held: First, a status and knowledge seminar; secondly, a future scenario seminar, and, finally, a roadmap seminar. The process involved around 40 seminars with more than 1600 participants and resulted in a number of suggestions and proposals on how each theme could contribute to the national targets.

The contributions involved a long list of energy demand side management and efficiency measures within households, industry and transportation, together 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 were described in relation to a Danish year 2030 "business as usual" reference (see below). Such description involved technical consequences as well as investment and operation and maintenance costs.

2.2 Analysis Methodology

In a parallel process, all the proposals were analysed technically in an overall energy system analysis using the computer model described below. The energy system analysis was conducted in the following steps:

First, the Danish Energy Authorities' official Business as Usual Scenario for year 2030 was re-calculated by use of the EnergyPLAN model, through which it was possible, on the basis of the same inputs, to come to the same conclusions regarding annual energy balances, fuel consumptions, and CO_2 emissions. Consequently, a common understanding of the reference was established.

Next, each of the proposals for year 2030 (mentioned above) was defined as a change of the reference system and a first rough alternative was calculated including all changes. Such a system leads to a number of imbalances both technically as well as economically, and consequently, proposals of negative feasibility were reconsidered and suitable investments in flexibility were added to the system.

In the model, the operation of the system is based on a business-economic optimisation of each production unit. Such optimisation includes taxes and involves electricity prices on the international electricity market.

The socio-economic consequences for Danish society do not include taxes. The consequences are based on the following basic assumptions:

- World market fuel costs equal an oil price of 68$/barrel (with a sensitivity of 40 and 98 $/barrel)
- Investment and operation costs are based on official Danish technology data, if available, and if not, based on the input from the "Energy Year" experts.
- An interest real rate of 3 per cent is used (with a sensitivity of 6 per cent)
- Environmental costs are not included in the calculation, apart from CO_2 emission trade prices of 20 EUR/ton (With a sensitivity of 40 EUR/ton).

Each individual proposal was analysed technically and a feasibility study was conducted. Since many of the proposals are not independent in nature, such analysis was conducted for each proposal, both in the reference "business as usual" system as well as in the alternative system. One proposal, e.g. the insulation of houses, may be feasible in the reference but not in the alternative system, if solar thermal is applied to the same houses or improved CHP (Combined Heat and Power) is also part of the overall strategy.

Consequently, several of the contributions and proposals had to be reconsidered and coordinated with other contributions.

2.3 The EnergyPLAN energy system analysis model

The overall energy system analysis and the feasibility studies of the project were carried out by researchers at Aalborg University using the energy system analysis model EnergyPLAN (see figure 2). The model has previously been used in a number of energy system analysis activities, including expert committee work for the Danish Authorities [28] and the design of 100 per cent renewable energy systems [12]. However, during the process of analysing the IDA Energy Plan, the model was improved and expanded into the present version 7.0 so that all contributions could be included in the analysis. Especially, the analyses of different transportation technologies were improved. Moreover, the modelling of socio-economic feasibility studies including exchange on international electricity markets was expanded.

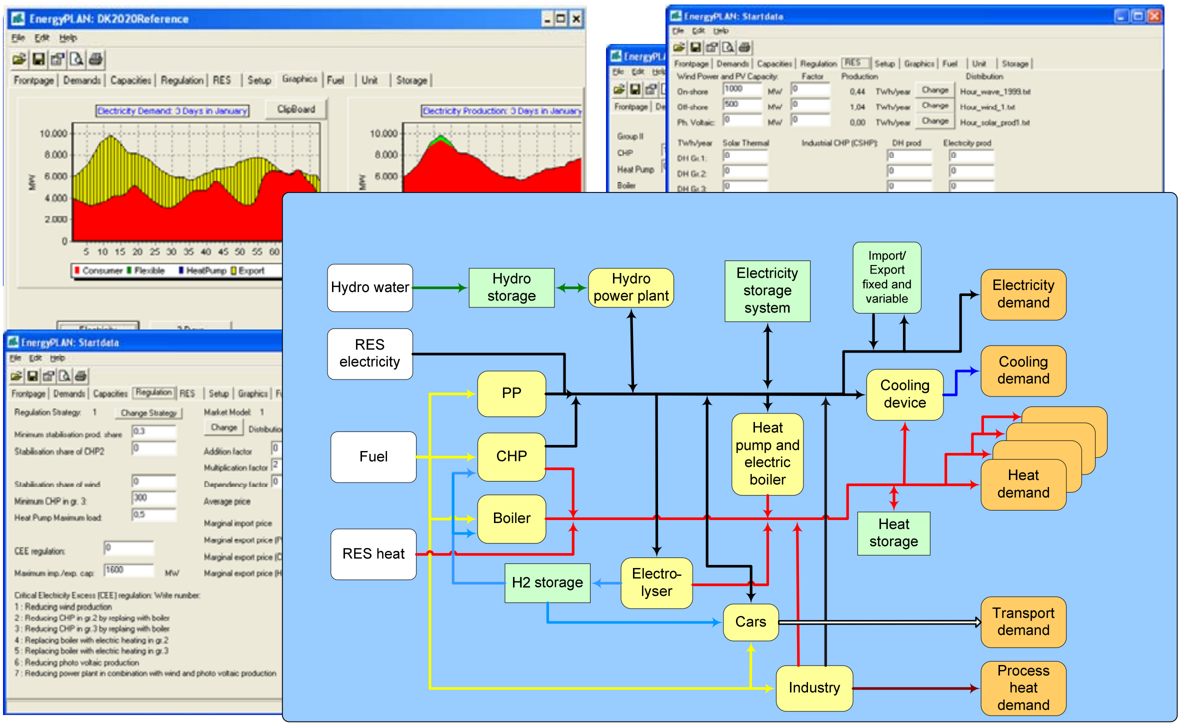


Figure 2. Flow diagram of energy technologies in the EnergyPLAN computer model

The energy system analysis of the EnergyPLAN model includes hour by hour simulations of the future Danish energy supply leading to the design of flexible energy systems with the ability to balance the electricity supply and demand and to exchange electricity productions on the international electricity markets. The methodology also includes the design of suitable feasibility studies of national energy systems in situations of fluctuating world market oil prices, CO2 quota trade prices, and electricity market prices.

Inputs include energy demands and renewable resources. For relevant demands such as electricity and district heating and relevant sources such as wind power and solar thermal, the inputs are distributed into hour by hour values using actual distribution from historical demands and productions.

More information on the model can be found in [31;32]

The present version 7.0 of the EnergyPLAN model including input data for the analysis of the IDA Energy Plan and documentation of the model can be downloaded freely from the following home page: www.EnergyPLAN.eu.

2.4 Input proposals to the IDA Energy Plan

The IDA Energy Plan is compared to both the present situation (of year 2004) and to a "business as usual" reference scenario year 2030, in which the gross energy consumption (primary energy supply) is expected to rise from 850 PJ in 2004 to 970 PJ in 2030.

The IDA Energy Plan is defined as a series of changes to the "business as usual" reference in 2030. The proposal is shown as both an alternative for year 2030 and a 100 per cent renewable alternative for year 2050. The different energy systems include everything, also natural gas consumption on the drilling platforms in the North Sea and jet petrol for international air transportation.

After completing the forward and back process of comparison and discussion between experts and overall systems analysis, the proposals for year 2030 ended up being the following:

- Reduce space heating demands in buildings by 50 per cent
- Reduce fuel consumption in industry by 40 per cent
- Reduce electricity demand by 50 per cent in private households and by 30 per cent in industry
- Supply 15 per cent of individual and district heating demand by solar thermal power
- Increase electricity production from industrial CHP by 20 per cent
- Reduce fuel consumption in the North Sea by 45 per cent through savings, CHP, and efficiency measures.
- Slow down the increase in transportation demands through tax reforms
- Replace 20 per cent of the road transportation by ships and trains.
- Replace 20 per cent of fuel for road transportation by biofuels and 20 per cent by electricity
- Replace natural gas boilers by micro fuel cell CHP, equal to 10 per cent of house heating
- Replace individual house heating by district heating CHP, equal to 10 per cent
- Replace future power plants constructed after 2015 by fuel cell CHP plants, equal to 35-40 per cent of total power plants in 2030
- Increase the total amount of biomass resources (including waste) from the present 90 PJ to 180 PJ in 2030.
- Increase wind power from the present 3000 MW to 6000 MW in 2030
- Introduce 500 MW wave power and 700 MW photovoltaic power
- Introduce 450 MWe large heat pumps in combination with existing CHP systems and flexible electricity demand in order to integrate wind power and CHP better in the energy system.

It should be emphasised that the proposal of adding heat pumps and flexible demand was an outcome of the overall energy systems analysis process, which also pointed out that the potential of flexible production (low minimum production requirements and ability to change production fast without loosing efficiency) from Solid Oxide Fuel Cell (SOFC) CHP and power plants should by exploited in the best possible way to overcome balancing problems in electricity and district heating supply.

In order to achieve a 100 per cent renewable energy supply, the following additional initiatives prolonging the 2030 energy system were proposed by the steering committee:

- Reduce the heat demands in buildings and district heating systems by another 20 per cent
- Reduce the fuel demand in industry by another 20 per cent
- Reduce the electricity demand by another 10 per cent
- Stabilise the transportation demand at the 2030 level
- Expand district heating by 10 per cent
- Convert micro CHP systems from natural gas to hydrogen
- Replace oil and natural gas boilers by heat pumps and biomass boilers in individual houses
- Replace 50 per cent of road goods transportation by train
- Replace remaining fuel demand for transportation equally by electricity, biofuels and hydrogen
- Supply 3 TWh of industrial heat production from heat pumps
- Replace all CHP and power plants by fuel cell-based or biogas or biomass gasification
- Supply 40 per cent of the heating demand of individual houses by solar thermal heat
- Increase wave power from 500 to 1000 MW
- Increase solar thermal power from 700 to 1500 MW

The necessary wind power and/or biomasses resources were calculated as the residual resources and had to be increased as described below.

3. RESULTS

The results are divided into the overall socio-economic feasibility study of the year 2030 system, the marginal feasibility of each individual proposal, and the energy balances, fuel consumptions, and CO2 emissions of both years 2030 and 2050.

3.1 Overall socio-economic feasibility and export potentials

The results of the socio-economic feasibility study and the export potentials are shown in figure 3.

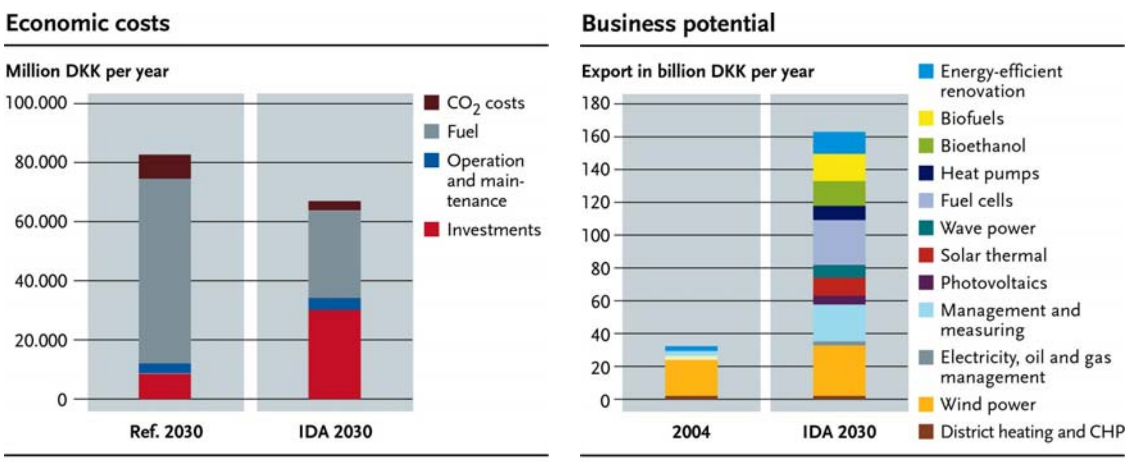


Figure 3. Economic costs and Business Potential of the IDA Energy Plan 2030

The bars to the left illustrate the economic costs related to Denmark's energy consumption and production in the reference and in the Danish Society of Engineers' (IDA) Energy Plan 2030. To the right, the Business potential of the IDA Energy Plan 2030 is shown, calculated as expected exports in 2030, compared to 2004.

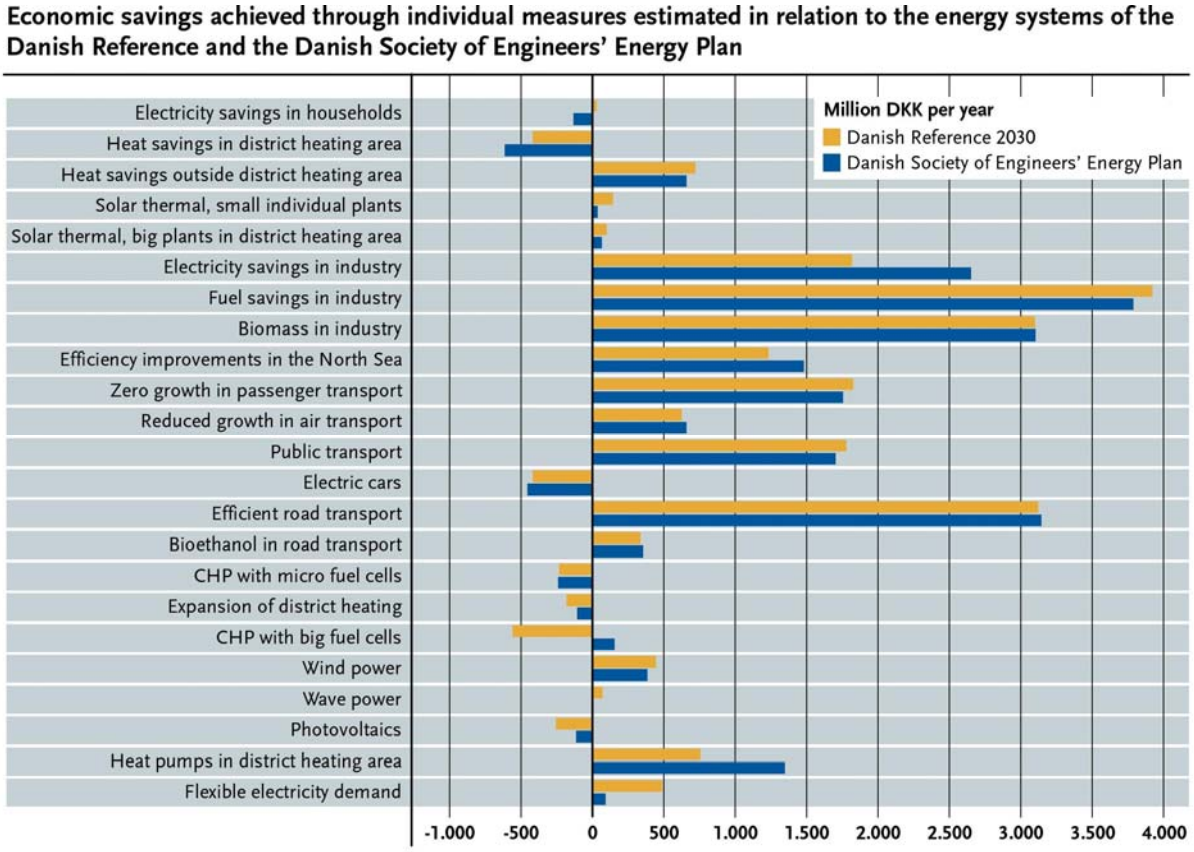
The socio-economic feasibility is calculated as annual costs including fuel and operation and annual investment costs based on a certain lifetime and interest rate. The feasibility study has been carried out with three different oil prices (as mentioned above) and the IDA Energy Plan 2030 is compared with the reference under the assumption that the average oil price is applicable 40 per cent of the time, while the low and high oil prices are applicable each 30 per cent of the time.

Compared to the reference, the IDA alternative converts fuel costs into investment costs and has lower total annual costs. Such a shift is very sensitive to two factors: The one is the interest rate and the other is the estimation of the magnitude of the total investment costs. Consequently, sensitivity analyses have been made: One in which the interest rate has been raised from 3 to 6 per cent, and another in which all investment costs have been raised by 50 per cent. In both cases, the IDA alternative is competitive to the reference.

The export potentials have been estimated on the basis of the Danish development of wind turbine manufacturing and are to be considered a very rough estimate. However, the estimate provides valuable information on both the different relevant technologies and the magnitude of the total potential.

3.2 Marginal feasibility of each proposal

The socio-economic feasibility and the CO2 emission of each proposal is shown in figure 4. All proposals have been evaluated marginally in both the reference system and the alternative system. As can be seen, the forward and back process has lead to the identification of proposals with predominantly positive feasibility. However, some proposals with negative feasibility have been included in the overall plan for other reasons. Some have good export potentials. Others are important in order to be able to reach the final target of 100 per cent renewable energy in the next step. And others again have important environmental benefits.



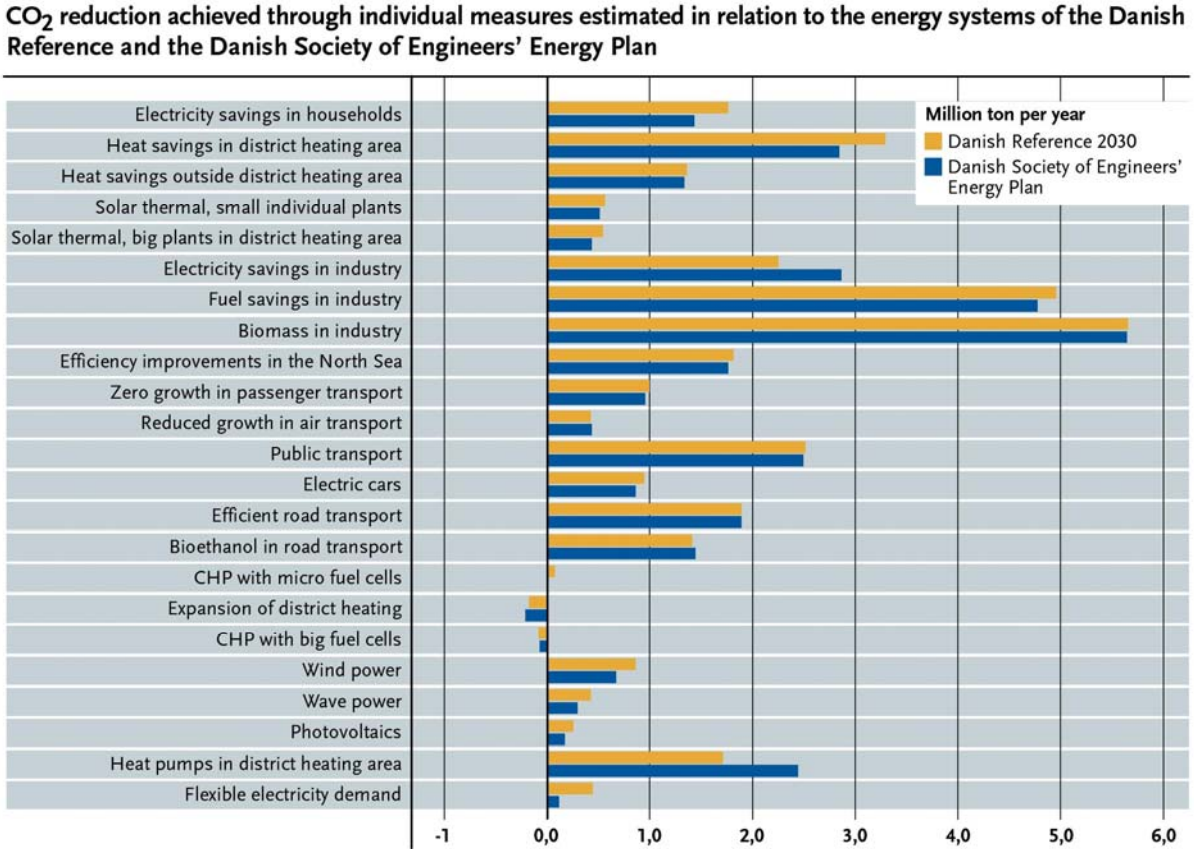


Figure 4. Feasibility and CO2 emission reduction of each of the individual proposals

3.3 100 per cent renewable energy system

The 100 per cent renewable energy system for year 2050 has been calculated in more than one version.

First, all the proposals mentioned above were simply implemented, which lead to a primary energy supply consisting of 19 PJ solar thermal, 23 PJ electricity from Renewable Energy Sources (wind, wave and photo voltaic) and 333 PJ biomass fuels. In such scenario, wind power is equal to the figure of year 2030, i.e. 6000 MW installed capacity.

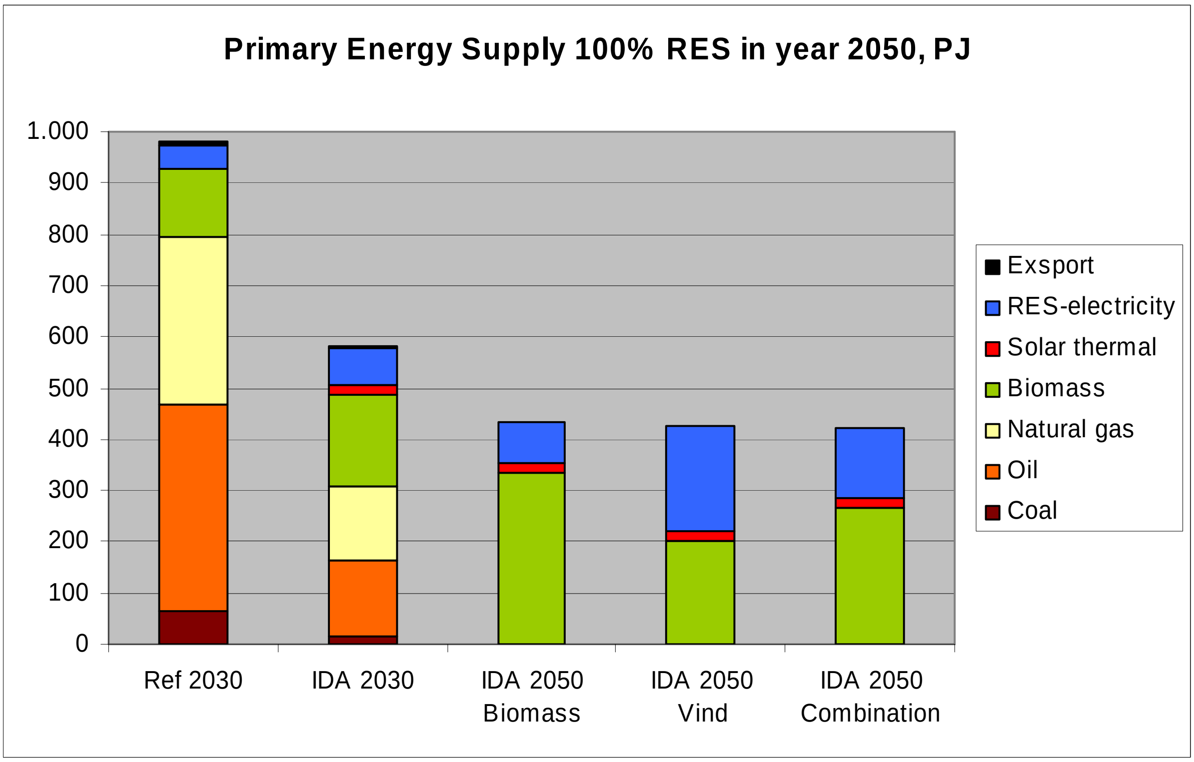


Figure 5. Primary Energy Supply for 3 versions of the 100 per cent renewable energy system compared to the reference and the IDA proposal for year 2030.

However, a figure of 333 PJ of biomass fuels may be too high. According to the latest official estimate, Denmark has approximately 165 PJ of residual biomass resources including waste. Residual resources comprise straw, which is not needed for animal purposes, together with biogas from manure, organic waste and waste from wood industries. However, the potential of biomass fuels from the change of crops is huge. E.g. Denmark grows a lot of wheat which can be replaced by others crops such as corn, leading to a much higher biomass production while still maintaining the same outputs for food. Such reorganisation of the farming areas together with a few other options may lead to a total biomass fuel potential as high as 400 PJ.

On the basis of the first version of the 100 per cent renewable energy scenario, it was analysed how much the need for biomass fuels would decrease if more wind power was added. If wind power is raised from 6000 MW to 15000 MW, then a rise in electricity to 200 PJ will lead to a decrease in biomass fuel consumptions to 200 PJ. It should, however, be emphasised that such replacement leads to a huge demand for hydrogen as an energy carrier, which results in considerable efficiency losses.

The analyses ended up proposing a compromise with 10,000 MW wind power and 270 PJ biomass fuels. All three versions are shown in figure 5. The energy flow of the system is illustrated in figure 6.

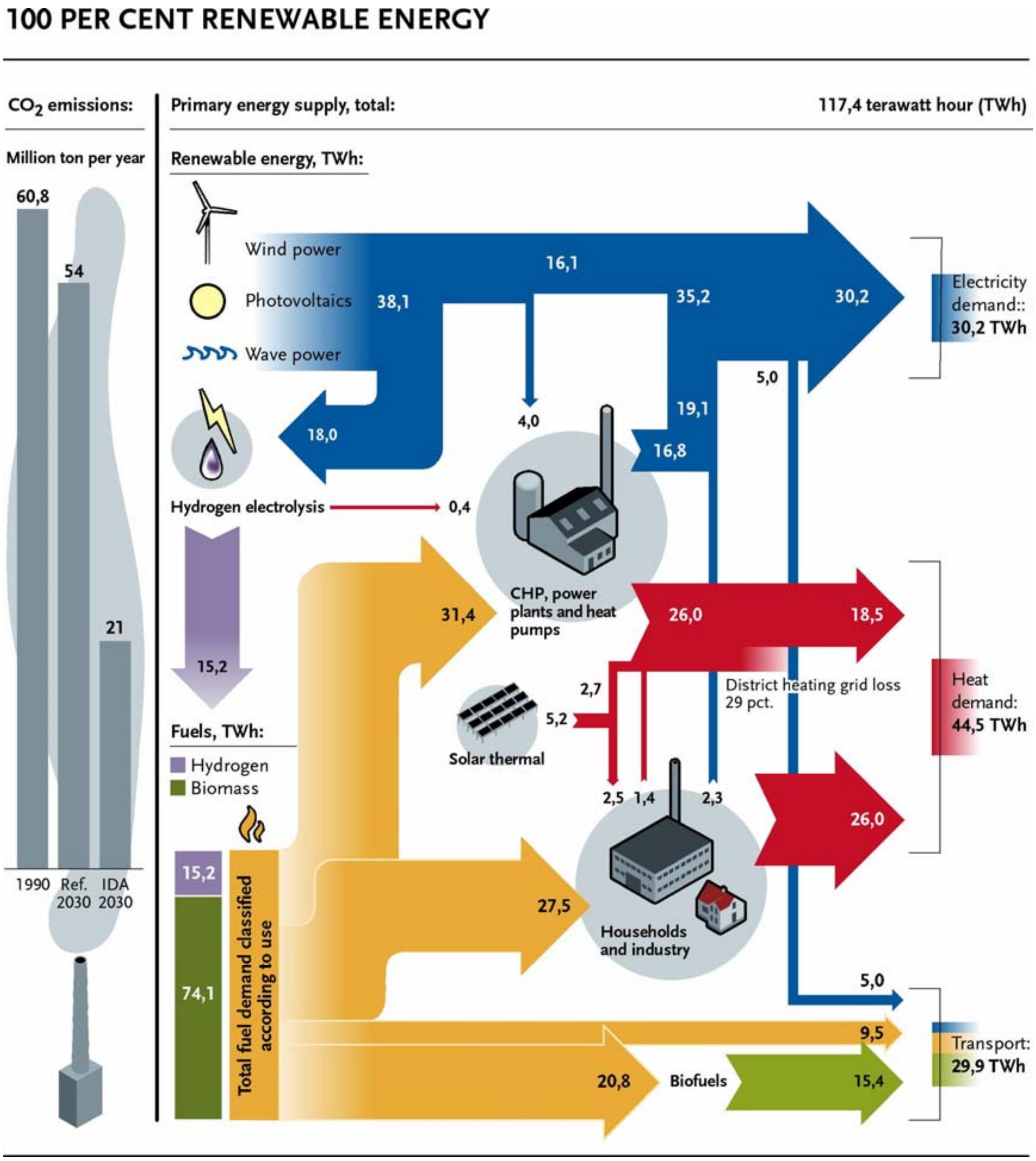


Figure 6. Flow diagram of the 100 per cent renewable energy system

3.4 Primary energy supply and CO2 emissions

The primary energy supply and the consequences related to CO2 emissions are shown in figure 7.

The primary energy supply is expected to increase from approximately 800 PJ in 2004 to nearly 1000 PJ in the “business as usual” reference. If the proposed IDA Energy Plan is implemented, the primary energy supply will fall to below 600 PJ and CO2 emissions will decrease by 60 per cent compared to year 1990.

If the 100 per cent renewable energy system proposed for year 2050 is implemented, the primary energy supply will fall to approximately 400 PJ and the CO2 emission will, in principle, be equal to zero. However, it should be mentioned that Denmark will still contribute to greenhouse gas emissions from other gasses than CO2. In total, the Danish greenhouse gas emissions will decrease by approximately 80 per cent.

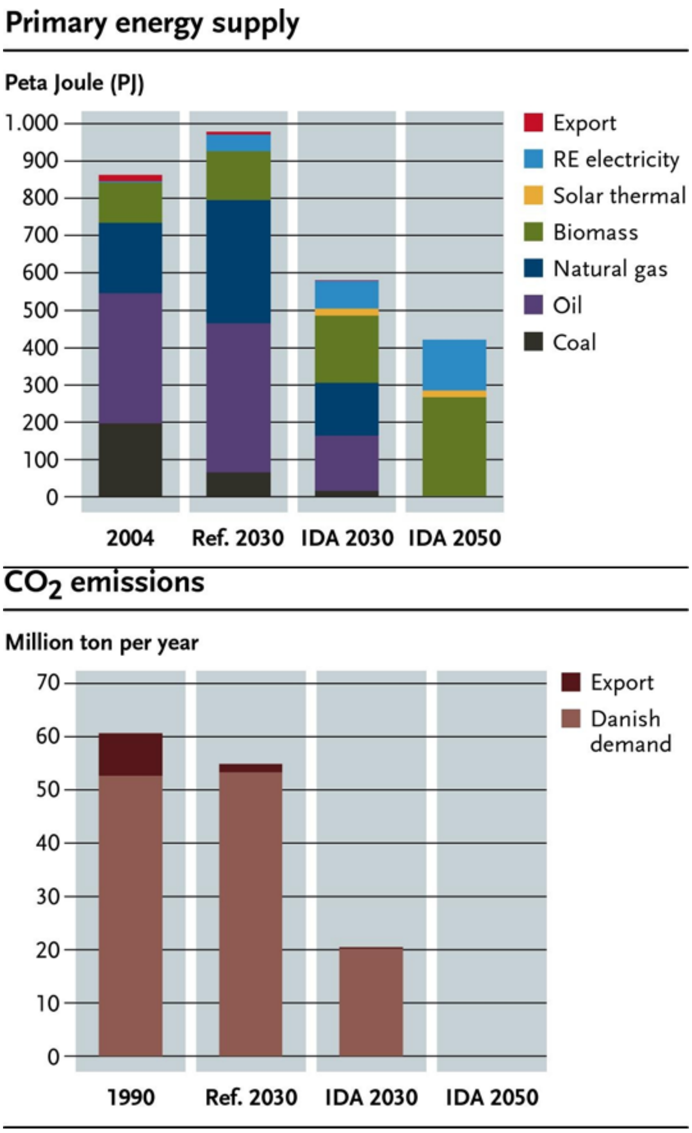


Figure 7. Primary energy supply and CO_2 emissions. CO_2 emissions are divided into domestic electricity demand and electricity net exports.

CONCLUSION

From a Danish case point of view, the conclusion is that a 100 per cent renewable energy supply based on domestic resources is physically possible, and that the first step toward 2030 is feasible to Danish society. However, Denmark will have to consider to which degree the country shall rely mostly on biomass resources, which will involve the present use of farming areas, or mostly on wind power, which will involve a large share of hydrogen or similar energy carriers leading to certain inefficiencies in the system design.

From a methodology point of view, the conclusion is that the design of future 100 per cent renewable energy systems is a very complex process. On the one hand, a broad variety of measures has to be combined in order to reach the target, and on the other hand, each individual measure has to be evaluated and coordinated with the new overall system. Here, such process has been achieved by the combination of a creative phase involving the inputs of a number of experts and a detailed analysis phase with technical and economic analyses of the overall system, giving feed-back on the individual proposals. In a forward and back process, each proposal was formed so that it combined the best of the detailed expert knowledge with the ability of the proposal to fit well into the overall system, both in terms of technical innovation, efficient energy supply and socio-economic feasibility.

ACKNOWLEDGEMENT

We would like to thank all participants in the IDA “Energy Year 2006”, whose inputs and expertise form the basis of the study. In particular, we would like to express our gratitude to the following persons, who formed the steering committee during the process and who took the initiative in inviting us to participate in the project: Søren Skibstrup Eriksen, Per Nørgaard, Kurt Emil Eriksen, John Schiøler Andersen, Thomas Sødring, Charles Nielsen, Hans Jørgen Brodersen, and Mogens Weel Hansen.

REFERENCES

[1] W. Clark and H. Lund, "Sustainable development in practice," *Journal of Cleaner Production*, vol. 15, no. 3, pp. 253-258, 2007.

[2] Danish Government, *Energy 21, The Danish Government´s Action Plan for Energy*. Copenhagen: Ministry of Environment and Energy, 1996.

[3] N. Duic and M. Graca Carvalho, "Increasing renewable energy sources in island energy supply: case study Porto Santo," *Renewable and Sustainable Energy Reviews*, vol. 8, no. 4, pp. 383-399, Aug.2004.

[4] European Council, *Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market*. Luxembourg: European Parliament, 2001.

[5] P. Hennicke, "Scenarios for a robust policy mix: the final report of the German study commission on sustainable energy supply," *Energy Policy*, vol. 32, no. 15, pp. 1673-1678, Oct.2004.

[6] F. Hvelplund and H. Lund, "Rebuilding without restructuring the energy system in east Germany," *Energy Policy*, vol. 26, no. 7, pp. 535-546, 1998.

[7] H. Lund, "A green energy plan for Denmark - Job creation as a strategy to implement both economic growth and a CO2 reduction," *Environmental & Resource Economics*, vol. 14, no. 3, pp. 431-439, 1999.

[8] H. Lund, F. Hvelplund, K. Ingermann, and U. Kask, "Estonian energy system - Proposals for the implementation of a cogeneration strategy," *Energy Policy*, vol. 28, no. 10, pp. 729-736, 2000.

[9] H. Lund, F. Hvelplund, and S. Nunthavorakarn, "Feasibility of a 1400 MW coal-fired power-plant in Thailand," *Applied Energy*, vol. 76, no. 1-3, pp. 55-64, 2003.

[10] H. Lund, G. Siupsinskas, and V. Martinaitis, "Implementation strategy for small CHP-plants in a competitive market: the case of Lithuania," *Applied Energy*, vol. 82, no. 3, pp. 214-227, Nov.2005.

[11] H. Lund, "Choice Awareness: The Development of Technological and Institutional Choice in the Public Debate of Danish Energy Planning," *Journal of Environmental Policy & Planning*, vol. 2: pp. 249-259, 2000.

[12] H. Lund, "Renewable energy strategies for sustainable development," *Energy*, vol. 32, no. 6, pp. 912-919, June2007.

[13] K. Blok, "Enhanced policies for the improvement of electricity efficiencies," *Energy Policy*, vol. 33, no. 13, pp. 1635-1641, Sept.2005.

[14] H. Lund, "Implementation of energy-conservation policies: the case of electric heating conversion in Denmark," *Applied Energy*, vol. 64, no. 1-4, pp. 117-127, 1999.

[15] N. Lior, "Advanced energy conversion to power," *Energy Conversion and Management*, vol. 38, no. 10-13, pp. 941-955, 1997.

[16] N. Lior, "Thoughts about future power generation systems and the role of exergy analysis in their development," *Energy Conversion and Management*, vol. 43, no. 9-12, pp. 1187-1198, 2002.

[17] N. H. Afgan and M. G. Carvalho, "Multi-criteria assessment of new and renewable energy power plants," *Energy*, vol. 27, no. 8, pp. 739-755, Aug.2002.

[18] N. H. Afgan and M. G. Carvalho, "Sustainability assessment of hydrogen energy systems," *International Journal of Hydrogen Energy*, vol. 29, no. 13, pp. 1327-1342, Oct.2004.

[19] X. Li, "Diversification and localization of energy systems for sustainable development and energy security," *Energy Policy*, vol. 33, no. 17, pp. 2237-2243, Nov.2005.

[20] T. Muneer, M. Asif, and S. Munawwar, "Sustainable production of solar electricity with particular reference to the Indian economy," *Renewable and Sustainable Energy Reviews*, vol. 9, no. 5, pp. 444-473, Oct.2005.

[21] R. Ghanadan and J. G. Koomey, "Using energy scenarios to explore alternative energy pathways in California," *Energy Policy*, vol. 33, no. 9, pp. 1117-1142, June2005.

[22] P. Alberg Ostergaard, "Transmission-grid requirements with scattered and fluctuating renewable electricity-sources," *Applied Energy*, vol. 76, no. 1-3, pp. 247-255, 2003.

[23] H. Lund, "Excess Electricity Diagrams and the Integration of Renewable Energy," *International Journal of Sustainable Energy*, vol. 23, no. 4, pp. 149-156, Dec.2003.

[24] H. Lund and P. A. Ostergaard, "Electric grid and heat planning scenarios with centralised and distributed sources of conventional, CHP and wind generation," *Energy*, vol. 25, no. 4, pp. 299-312, 2000.

[25] H. Lund and W. W. Clark, "Management of fluctuations in wind power and CHP comparing two possible Danish strategies," *Energy*, vol. 27, no. 5, pp. 471-483, 2002.

[26] H. Lund and E. Münster, "Management of surplus electricity-production from a fluctuating renewable-energy source," *Applied Energy*, vol. 76, no. 1-3, pp. 65-74, 2003.

[27] H. Lund, "Large-scale integration of optimal combinations of PV, wind and wave power into the electricity supply," *Renewable Energy*, vol. 31, no. 4, pp. 503-515, Apr.2006.

[28] H. Lund and E. Munster, "Integrated energy systems and local energy markets," *Energy Policy*, vol. In Press, Corrected Proof.

[29] H. Lund, "Large-scale integration of wind power into different energy systems," *Energy*, vol. 30, no. 13, pp. 2402-2412, Oct.2005.

[30] H. Lund and E. Munster, "Integrated transportation and energy sector CO2 emission control strategies," *Transport Policy*, vol. 13, no. 5, pp. 426-433, Sept.2006.

[31] H. Lund and E. Münster, "Modelling of energy systems with a high percentage of CHP and wind power," *Renewable Energy*, vol. 28, no. 14, pp. 2179-2193, 2003.

[32] H. Lund, "EnergyPLAN Advanced Energy System Analysis Model," Aalborg University, www.energyPLAN.eu, Denmark,Apr.2007.