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Renewable energy strategies for sustainable development

Henrik Lund*

Department of Development and Planning, Aalborg University, Fibigerstraede 13, 9220 Aalborg, Denmark

Abstract

This paper discusses the perspective of renewable energy (wind, solar, wave and biomass) in the making of strategies for a sustainable development. Such strategies typically involve three major technological changes: energy savings on the demand side, efficiency improvements in the energy production, and replacement of fossil fuels by various sources of renewable energy. 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. Based on the case of Denmark, this paper discusses the problems and perspectives of converting present energy systems into a 100% renewable energy system. The conclusion is that such development is possible. The necessary renewable energy sources are present, and if further technological improvements of the energy system are achieved the renewable energy system can be created. Especially technologies of converting the transportation sector and the introduction of flexible energy system technologies are crucial.

Keywords: Energy systems; Renewable energy; Flexible energy systems

1. Introduction

Sustainable Energy Development Strategies typically involve three major technological changes: energy savings on the demand side [1,2], efficiency improvements in the energy production [3,4], and replacement of fossil fuels by various sources of renewable energy [5,6]. 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 [7–10].

First, the major challenge is to expand the amount of renewable energy in the supply system. Renewable energy is considered an important resource in many countries around the world [11–18], but as illustrated in Fig. 1, on a global scale less than 15% of primary energy supply is renewable energy, and the major part is hydro power and wood fuels in developing countries. Renewable sources, such as wind and solar, only constitute a very small share of the total supply. However, the potential is substantial. And in some regions and countries, the share of renewable energy has grown substantially during the last couple of decades. Two major challenges of renewable energy strategies for sustainable development can be identified. One challenge is to integrate a high share of intermittent resources into the energy system, especially the electricity supply [19,20]. The other is to include the transportation sector in the strategies [21,22]. Based on the case of Denmark, this paper describes the challenges and discusses the potential solutions to these challenges.

In Denmark, savings and efficiency improvements have been important parts of the energy policy since the first oil crisis in 1973. Hence, by means of energy conservation and expansion of Combined Heat and Power production (CHP) and district heating, Denmark has been able to maintain the same primary fuel consumption for a period of more than 30 years in spite of about 70% increase in GDP. Moreover, 14% of fossil fuels have been replaced by renewable energy. In the same period, both transportation and electricity consumption as well as the heated space area have increased substantially.

Thus, Denmark is an example of how sustainable development strategies constituted by a combination of savings, efficiency improvements and renewables can be implemented. Consequently, Denmark is now facing the

*Tel.: +45 96 35 83 09; fax: +45 98 15 37 88.
E-mail address: Lund@plan.aau.dk.

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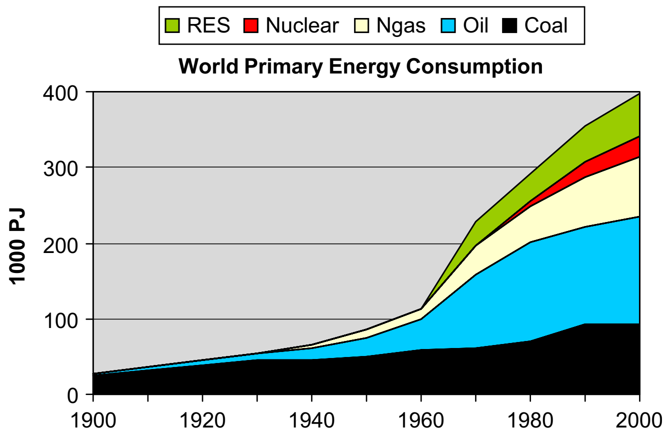

Fig. 1. World primary energy supply based on [42].

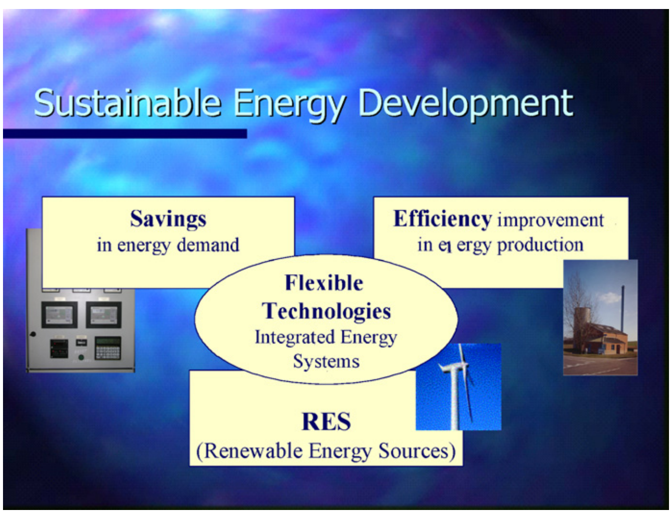

Fig. 2. Sustainable energy development.

two problems of integrating the high share of intermittent electricity from Renewable Energy Sources (RES) and including the transportation sector in the future strategies. Hence, reaching this stage of making sustainable energy strategies the issue is not only a matter of savings, efficiency improvements and renewables. It also becomes a matter of introducing and adding flexible energy technologies and designing integrated energy system solutions. Such technological changes are necessary in order to bring about further sustainable development as illustrated in Fig. 2.

The Danish Energy Agency has estimated the realistic biomass potential for energy purposes to 20–25% of the present total primary energy supply. Meanwhile, Denmark has a great potential for other sorts of renewable energy, especially wind power. Therefore, Denmark is in many ways a typical example of the situation in many countries: the transportation sector is totally fuelled by oil, the biomass potential is not big enough to replace fossil fuels, but the potential of intermittent renewable sources is substantial.

Based on the case of Denmark, this paper discusses the problems and perspectives of converting present energy systems into a 100% renewable energy system.

2. Potential renewable energy sources in Denmark

The potential of renewable energy sources in Denmark was estimated by the Danish Energy Agency in 1996 as part of the data which provides the basis of the Danish Government energy plan "Energy 21"[23]. The estimate, which is shown in Table 1, dates back 10 years, and today, it seems that some potential is underestimated. Especially the offshore wind potential, which is very dependent on the technological development, is considered higher today and will increase in the future along with the growth in size of the wind turbines. Furthermore, it should be noted that the

Table 1
Potential renewable energy sources in Denmark (Danish Energy Agency, 1996)

Renewable energy source	Potential
Wind (onshore)	5–24 TWh/yr
Wind (offshore)	15–100 TWh/yr
Photo Voltaic (10–25% of houses, 100–200 kWh/m^2)	3–16 TWh/yr
Wave energy	17 TWh/yr
Hydro power	~0 TWh/yr
Total electricity	40–160 TWh/yr
Solar thermal (individual houses)	6–10 PJ/yr
Solar thermal (district heating)	10–80 PJ/yr
Geothermal	>100 PJ/yr
Total heat	100–200 PJ/yr
Straw	39 PJ/yr
Wood	23 PJ/yr
Waste (burnable)	24 PJ/yr
Biogas	31 PJ/yr
Energy crops	65 PJ/yr
Total biomass fuel	182 PJ/yr

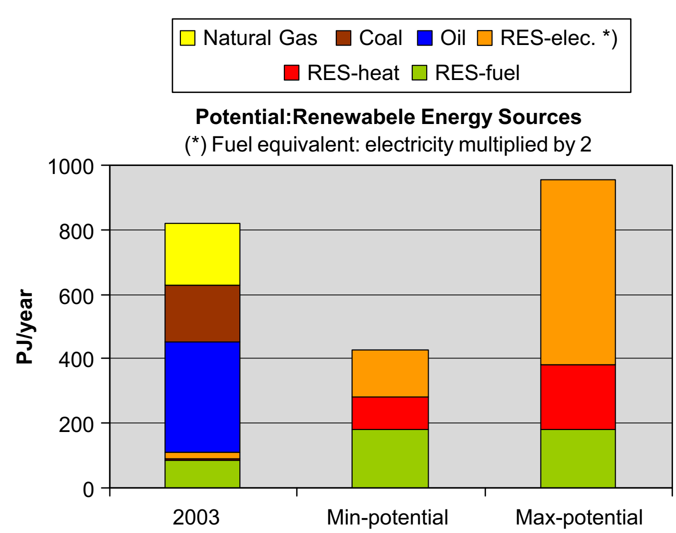

Fig. 3. Potential of RES in Denmark [20] compared to the primary energy consumption in 2003.

theoretical biomass potential is as high as 530 PJ/yr, if all farming areas are converted into energy crops, and 310 PJ/yr in the case that Denmark is self-supplied by food and the rest of the areas are converted into energy crops. Thus, the potential of a total of 180 PJ/yr including only a minor share of energy crops is to be considered a "business as usual" scenario in terms of food production.

Thus, the potentials are substantial, and only a small share is utilised today. In Fig. 3, the minimum and maximum potentials are compared to the present fuel consumption in Denmark.

3. Reference scenario

Danish energy supply is traditionally based on fossil fuels. Denmark has very little hydro power potential and during the 60 and 70 s, the electricity supply was dominated by large steam turbines located near the big cities. However, after the first oil crisis, Denmark has become a leading country in terms of implementing CHP, energy conservation and renewable energy. Consequently, the Danish energy system has been changed from a situation in 1972, in which 92% out of a total of 833 PJ was oil, into a situation of today in which only 41% out of 828 PJ is oil. In the same period, both transportation and electricity consumption as well as the heated space area have increased substantially. Today, the share of electricity production from CHP is as high as 50%, and approximately 20% of the electricity demand is supplied by wind power [24–29]. Fig. 4 illustrates the development from 1972 until today and shows the outlook for the future in accordance with the reference scenario explained in the following.

When analysing the possibilities of continuing the development and replacing more fossil fuels by renewable energy, two problems arise.

One problem is the transportation sector, which is almost totally fuelled by oil. Consumptions have been increasing from 140 PJ in 1972 to an expected 180 PJ or more in 2020. Thus, the transportation sector accounts for almost all of the expected oil consumption.

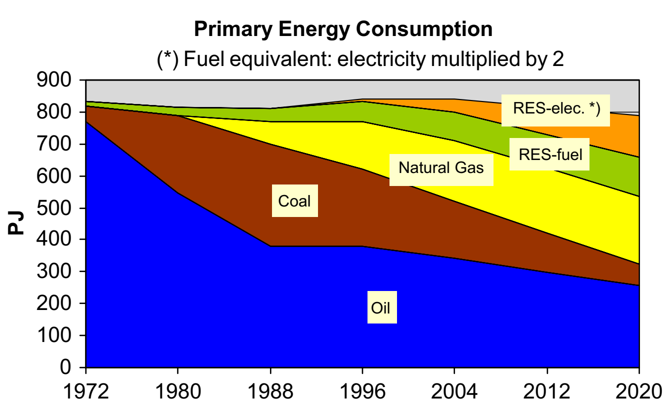

Fig. 4. Primary energy consumption in Denmark including expectations to the future.

The other problem is the integration of electricity production from CHP and wind power. Until recently, the CHP plants have not been operated to balance fluctuations in wind power and consequently, Denmark has had problems of excess electricity production in periods of strong winds.

In 2001, on request of the Danish Parliament, the Danish Energy Agency formed an expert group to investigate the problem of excess electricity production arising from the high per cent of wind power and CHP in the Danish energy system [30]. As part of the work, Aalborg University made a series of long-term year 2020 energy system analyses of investments in more flexible energy systems in Denmark [31]. These analyses were carried out by use of the EnergyPLAN energy system analysis computer model [32–34]. As a reference for the analysis, the expert group defined a Danish future year 2020 energy system in accordance with Danish long-term energy policies and strategies.

Compared to the present situation, the reference is assuming the following development:

- The Danish electricity demand is expected to rise from 35 TWh in year 2001 to 41 TWh in year 2020 equal to an annual rise of approximately 0.8%.
- The installed capacity of wind power in year 2001 is expected to rise from 570 to 1850 MW in East Denmark and from 1870 to 3860 MW in West Denmark in the year 2020. The increase is primarily due to the implementation of one 150 MW offshore wind farm each year.
- Existing large coal-fired CHP steam turbines are replaced by new natural gas-fired combined cycle CHP units when the lifetime of the old CHP plants exceeds. Additionally, small CHP plants and industrial CHP are due to a small expansion.

In 2001, the expert group conducted the analyses separately on the western and the eastern parts of Denmark, which have separate electricity grids. For

Table 2
Reference energy system: Denmark year 2020

Reference energy system: Denmark year 2020	
Key figure	
Electricity demand	41.1 TWh/yr
District heating demand	30.0 TWh/yr
Excess electricity production	8.4 TWh/yr
Primary energy supply	
Wind power	17.7 TWh/yr
Fuel for CHP and power plants	92.3 TWh/yr
Fuel for households	19.7 TWh/yr
Fuel for industry	20.2 TWh/yr
Fuel for transport	50.7 TWh/yr
Fuel for refinery, etc.	17.4 TWh/yr
Total	218.0 TWh/yr

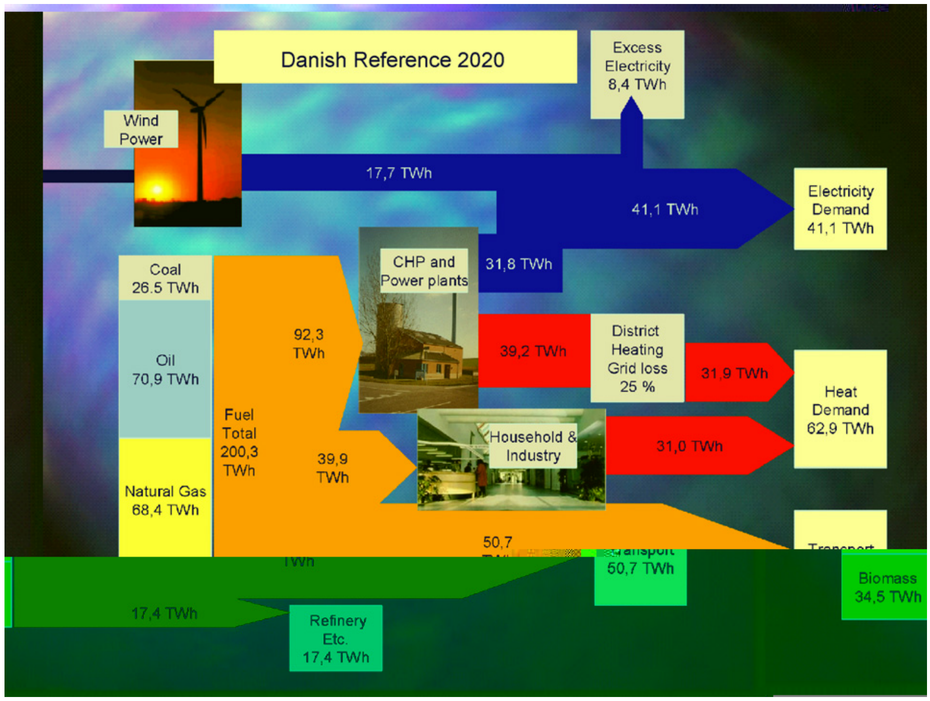

Fig. 5. Principle diagram of the energy flow in the Danish reference energy system year 2020.

practical reasons the analysis in the following has been made for a joined system including all of Denmark. Moreover, the expert group only included analyses of the electricity system. Consequently, data for the rest of the sectors including the transport sector have been added on the basis of the official Danish energy plan "Energy 21".

The reference scenario was illustrated previously in Fig. 4 and the main figures are shown in Table 2. A diagram of the energy flows in the system is given in Fig. 5.

4. Methodology

The aim of the analysis is to evaluate whether a 100% renewable energy system is a possibility for Denmark and to identify key technological changes and suitable implementation strategies.

All changes have been calculated by use of the EnergyPLAN energy system analysis model. Consequently, the energy balance of each system has been calculated for each hour of the year taking into account the intermittent nature of RES, limitations in capacities of flexible technologies as well as demands for ancillary services.

The EnergyPLAN model has been used for a number of similar analyses of large-scale integration of renewable energy [33,35–39].

4.1. Sustainable energy system technologies

The starting point for the analysis is the key assumption that sustainable development involves three major technological changes, namely energy savings on the demand side, efficiency improvements in the energy production, and replacement of fossil fuels by various sources of renewable energy. Consequently, the three following technological changes have been identified for the analysis.

Savings: A 10% decrease in the demand of electricity, district heating and the heating demand in households and industry.

Efficiency: A combination of better efficiencies and more CHP. Better efficiencies are defined as 50% electric output and 40% heat output of CHP plants. This can be achieved either by partial implementation of fuel-cell technology or by improvements of existing steam-turbine/engine technologies. More CHP is defined as a 50% of fuels for individual houses and industry being converted into CHP partly by district heating.

RES (renewable energy sources): Increasing the biomass fuels from 34 to 50 TWh/yr (125–180 PJ/yr) and adding 2.1 TWh solar thermal to district heating and 5000 MW of photo-voltaics to the electricity production.

All: A combination of the three measures described above.

It should be noted that such technological changes are moderate compared to the maximum potential. Thus, it is both possible and realistic to save more than 10% as well as to replace more than 50% by CHP, etc.

4.2. Flexible technologies

When increasing savings, efficiency measures and renewables the problem of integration becomes important and so does the issue of including transportation. Consequently, the following improvements of system flexibility have been defined for the analysis:

Transport: Oil for transportation is replaced by electricity consumption according to a scenario described by Risø National Laboratory [40]. Vehicles weighing less than 2 t are transformed into a combination of battery vehicles and hydrogen fuel cell vehicles. In the scenario, 20.8 TWh of oil is replaced by 7.3 TWh of electricity. Here, the same ratio has been used for converting the total oil consumption of 50.7 TWh in the reference scenario into an electricity consumption of 17.8 TWh. The electricity demand has been made flexible within a week and with a maximum capacity of 3500 MW.

Flexible CHP and heat pumps: The next step is to include small CHP plants in the regulation as well as adding heat pumps to the system. A 1500 MWe Heat Pump capacity with a COP of 3.5 has been analysed.

Electrolysers and wind regulation: The final step is to add electrolysers to the system and at the same time provide for the inclusion of wind turbines in the voltage and frequency regulation of the electricity supply.

The three measures and their technical designs are described in more details in [39,41].

5. Results

First, the consequences of each of the three sustainable technological changes have been analysed as well as the combination of the three. The results are shown in Fig. 6 in terms of primary energy consumption.

Fig. 6 shows that the tendency is an increase in the fuel consumption rather than a decrease. This is due to the fact that such technological changes lead to a substantial increase in the electricity excess production. More CHP, better efficiencies, less demand (savings) and more intermittent resources all lead to a higher excess production unless something is done to prevent such problems. The resulting excess productions are given in Table 3.

The general tendency is that the intention to decrease fossil fuels leads to an increased excess production.

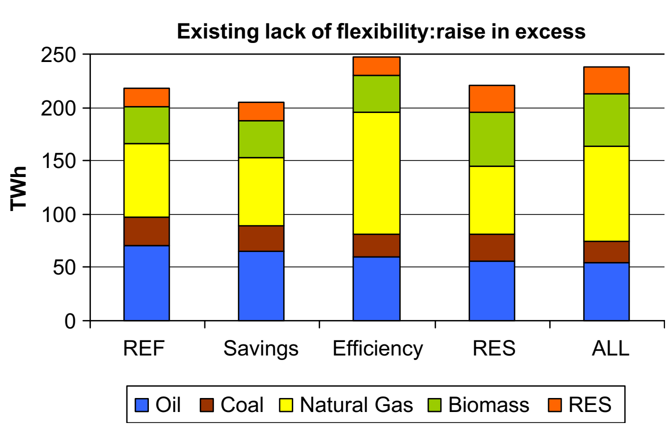

Fig. 6. Primary energy consumption year 2020 in the reference compared to the three technological changes including electricity excess production.

One way of avoiding the excess electricity production is to utilise it for domestic purposes. Here, such analysis has been carried out for the following priority: In the case of excess production, the CHP units are first replaced by boilers, secondly, boilers are replaced by electric heating, and thirdly, the production from wind turbines and/or photo-voltaics is simply reduced. This is a rather simple and inexpensive way of avoiding excess production; the results are shown in Fig. 7.

Now, all technological improvements result in a decrease in fuel consumption. However, the decrease is small since most of the benefit of the technological improvements is lost in the excess production problem. Another problem is the high share of oil for transportation. Consequently, the first step of flexibility is to convert all transportation fuel from oil to electricity, as described in the previous section and shown in Fig. 8. In this case, both the reference and all the alternatives result in a decrease in fuel consumption.

The final step in the analysis has been to add better flexibility in terms of heat pumps and CHP regulation together with electrolysers as described in the previous section. Hereafter, the RES alternative has been combined with the other measures and finally wind power has been added to the system until the resulting fuel consumption was equal to the available biomass resources of 180 PJ (50 TWh)/yr. The results are given in Fig. 9.

In this case, the main question is how much wind power is needed in order to fulfil the objective. The resulting wind power capacity is given in Table 4. As seen, the Danish energy system can be converted into a 100% renewable energy system when combining 180 tJ/yr of biomass with

Table 3
Resulting fuel consumption and excess electricity production for the alternatives in year 2036 compared to the reference year 2020

TWh/yr	REF	Savings	Efficiency	RES	All
Total fuel consumption	218	205	248	220	238
Electricity excess	8.4	9.6	45.5	11.7	48.2

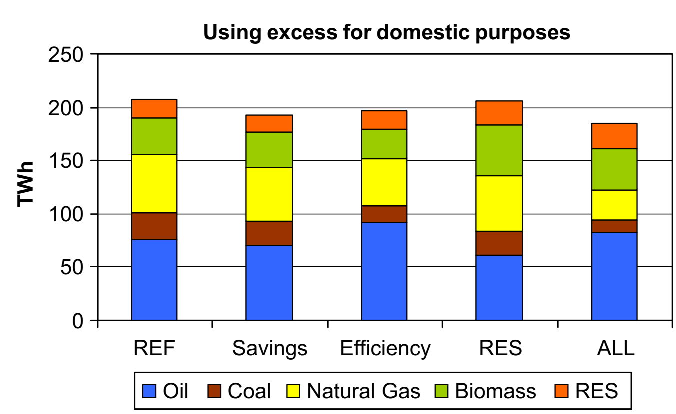

Fig. 7. Same as Fig. 6 but without electricity excess production (the excess production is used to replace fuels).

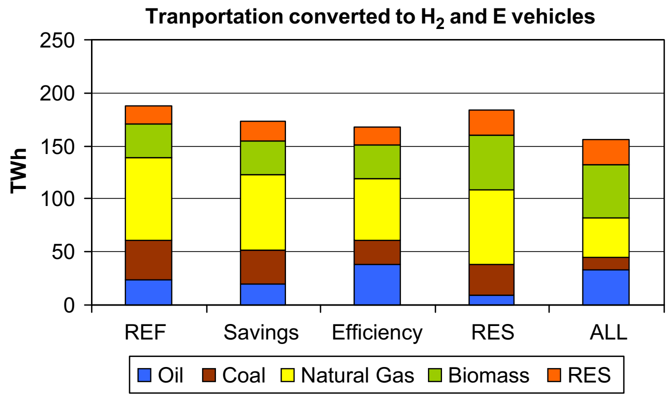

Fig. 8. Primary energy consumption (same as Fig. 7) when oil for transportation is replaced by electricity for electric vehicles and hydrogen vehicles.

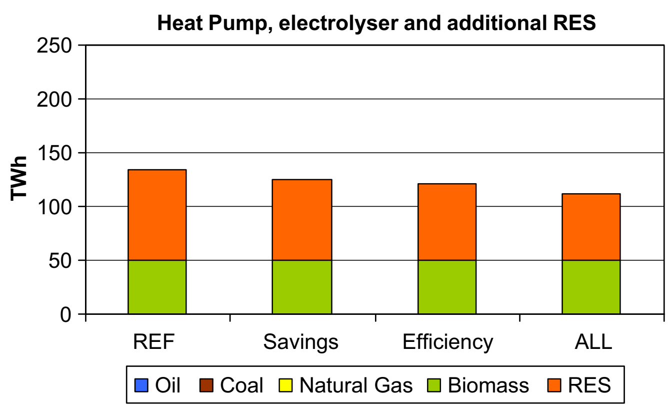

Fig. 9. Primary energy consumption (same as Fig. 8) when converting to 100 per cent RES.

Table 4
Resulting fuel consumption and needed wind capacity

TWh/yr	REF	Savings	Efficiency	All
Total fuel consumption (TWh/yr)	134	125	121	112
Wind power (GW)	27.1	22.1	18.6	15.6
Annual wind cap. (MW/yr) Lifetime = 30 years	900	740	620	520

5000 MW photo-voltaics and between 15 and 27 GW of wind power.

In the reference, 27 GW wind power is necessary, while in the combination with savings and efficiency improvements, the necessary capacity is reduced to 15 GW.

With an expected average lifetime of 30 years of new offshore wind power a total capacity of 15 GW can be reached by installing 500 MW/yr. Subsequently, the 15 GW can be maintained by a continuous replacement of 500 MW each year. Since 3 GW has already been installed, the total capacity can be reached within approximately 25 years, i.e. in year 2030.

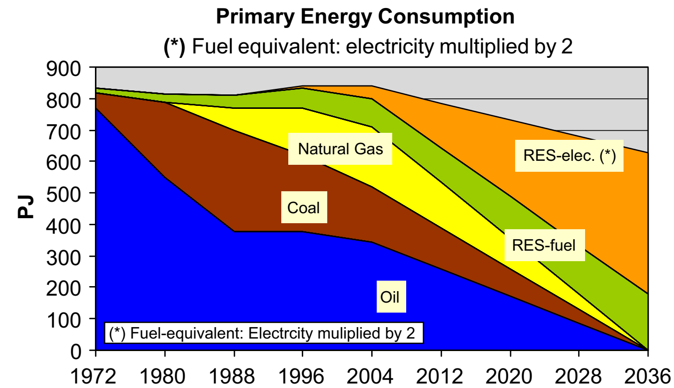

Fig. 10. Primary fuel consumption if Danish energy system is converted into 100 per cent RES.

In Figs. 10 and 11, the primary fuel consumption and the energy flow of such a system are illustrated. The two figures are comparable to the previous Figs. 4 and 5.

6. Conclusion

Sustainable Energy Development Strategies typically involve three major technological changes: energy savings on the demand side, efficiency improvements in the energy production, and replacement of fossil fuels by various sources of renewable energy. 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.

However, when reaching a high share of intermittent resources in combination with CHP and savings, the making of sustainable energy strategies becomes a matter of introducing and adding flexible energy technologies and designing integrated energy system solutions. Such technological changes are required in order to generate further sustainable development.

Based on the case of Denmark, this paper has discussed the problems and perspectives of converting present energy systems into a 100% renewable energy system.

The aim of the analysis is to analyse whether a 100% renewable energy system is a possibility for Denmark and to identify key technological changes and suitable implementation strategies.

All changes have been calculated using the EnergyPLAN energy system analysis model. The energy balance of each system has been calculated for each hour of the year taking into account the intermittent nature of RES, limitations in capacities of flexible technologies as well as demands for ancillary services.

The following improvements of system flexibility have been identified as being essential to the conversion of the energy system into a 100% renewable system:

First, oil for transportation must be replaced by other sources. Given the limitations in Danish biomass resources, solutions based on electricity become key technologies.

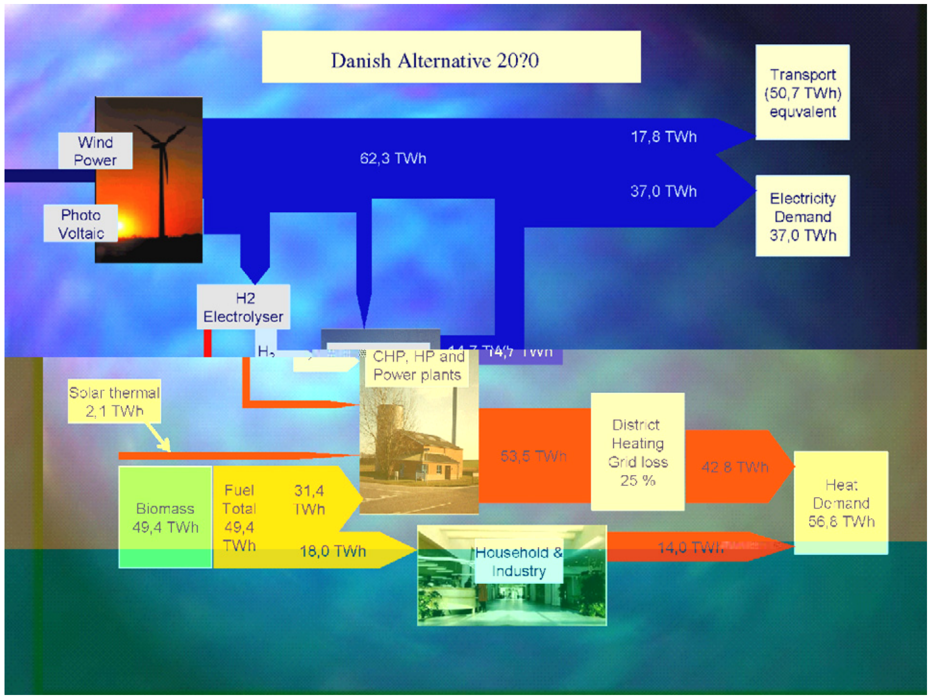

Fig. 11. Principle diagram of the energy flow in a 100 per cent Danish renewable energy system.

Moreover, such technologies increase the potential of including wind power in the ancillary services of maintaining voltage and frequency in the electricity supply.

The next key point is to include small CHP plants in the regulation as well as adding heat pumps to the system. Such technologies are of particular importance since they provide for the possibility of changing the ratio between electricity and heat demand while still maintaining the high fuel efficiency of CHP.

The third key point is to add electrolysers to the system and at the same time provide for a further inclusion of wind turbines in the voltage and frequency regulation of the electricity supply.

By implementing the three key technological changes the analyses show that the Danish energy system can be converted into a 100% renewable energy system when combining 180 TJ/yr of biomass with 5000 MW photovoltaics and between 15 and 27 GW of wind power. In the reference, 27 GW wind power is necessary, while in combination with savings and efficiency improvements the needed capacity is reduced to around 15 GW.

15 GW wind power can be reached by installing 500 MW/yr. Today Danish manufactories produce approximately 3000 MW wind power per year.

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