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Published in:
3rd Dubrovnik conference on sustainable development of energy, water and environment systems

Publication date:
2005

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

Renewable Energy Strategies for Sustainable Development

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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 of how to integrate the 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 percent renewable energy system. The conclusion is that such development will be possible. The necessary renewable energy sources are present, if further technological improvements of the energy system are achieved. Especially technologies of converting the transportation and the introduction of flexible energy system technologies are crucial.

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 of how to integrate the renewable sources in coherent energy systems influenced by energy savings and efficiency measures [7-9].

First, the major challenge is to expand the amount of renewable energy. Renewable energy is considered an important resource in many countries around the world [10-17], but as illustrated in figure 1 on a global scale less than 15 percent of primary energy consumption is renewable energy, and the major part is hydro power and wood fuels in development countries. Renewable sources such as wind and solar constitutes only a very small share of the total consumption. However, the potential is substantial. And in some regions and countries the share of renewable energy has grown substantially during the recent couple of decades, and two major challenges of renewable energy strategies for sustainable development can be identified. The one is to integrate a high share of intermittent resources into the energy system, especially the electricity supply [18]. The other is to include the transportation sector in the strategies [9]. Based on the case of Denmark this paper describes the challenges and discusses potential solutions.

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In Denmark savings and efficiency improvements have been important parts of the energy policy since the first oil crisis in 1972. Hence, by means of energy conservation and expansion of CHP and district heating Denmark has been able to maintain the same primary fuel consumption for a period of more than 30 years. Moreover, 14 percent of fossil fuels have been replaced by renewable energy. In the same period both transportation, electricity consumption as well as the area of heated space have increased substantially.

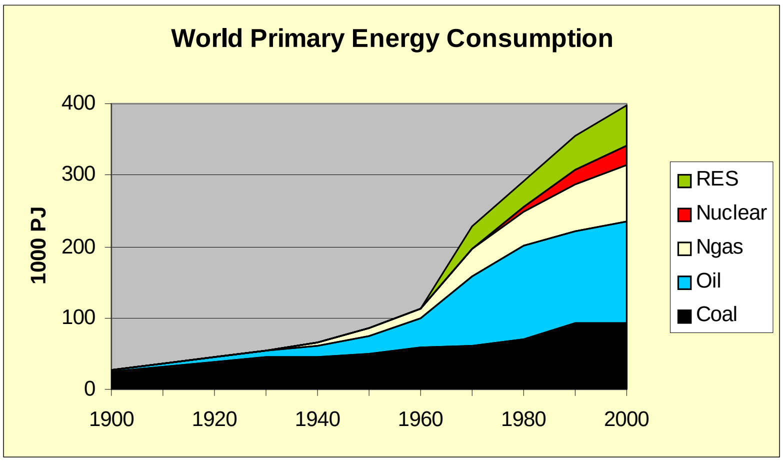

Fig. 1. World primary energy supply based on [19].

Thus, Denmark is an example of implementing sustainable development strategies constituted by a combination of savings, efficiency improvements and renewables. And consequently Denmark is now facing the two problems of integrating the high share of intermittent electricity from 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 systems solutions. Such technological changes are necessary in order to bring about further sustainable development as illustrated in figure 2.

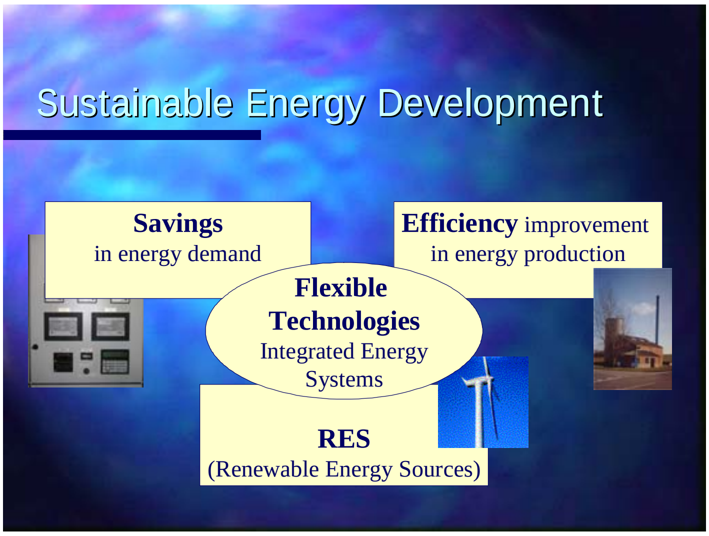

Fig. 2. Sustainable Energy Development

The Danish Energy Agency has estimated the realistic biomass potential for energy purposes to 20-25 percent of the present total primary energy supply. Meanwhile, Denmark has a huge potential for other sorts of renewable energy, especial wind power. Therefore Denmark is in many ways typical for the situation in many countries: 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 are substantial.

Based on the case of Denmark, this paper discusses the problems and perspectives of converting present energy systems into a 100 percent 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 material behind the Danish Government energy plan "Energy 21"[20]. The estimate, which is shown in table 1, is ten years old, and already now it seems that some potential is underestimated. Especial 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 the size of wind turbines. Also it should be noted that the theoretical biomass potential is as high as 530 PJ/year, if all farming areas are converted to energy crops and 310 PJ/year in the case of Denmark being self-supplied by food and converted the rest of the area to energy crops. Thus, the potential of a total of 180 PJ/year including only a minor share of energy crops is to be considered a "business as usual" scenario in terms of food production.

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

Renewable Energy Source	Potential
Wind (onshore)	5 - 24 TWh/year
Wind (offshore)	15 – 100 TWh/year
Photo Voltaic (10-25% of houses, 100-200 kWh/m2)	3 – 16 TWh/year
Wave Energy	17 TWh/year
Hydro power	~ 0 TWh/year
Total Electricity	**40 - 160 TWh/year**
Solar thermal (individual houses)	6-10 PJ/year
Solar thermal (district heating)	10-80 PJ/year
Geothermal	> 100 PJ/year
Total Heat	**100-200 PJ/year**
Straw	39 PJ/year
Wood	23 PJ/year
Waste (burnable)	24 PJ/year
Biogas	31 PJ/year
Energy crops	65 PJ/year
Total Biomass fuel	**182 PJ/year**

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

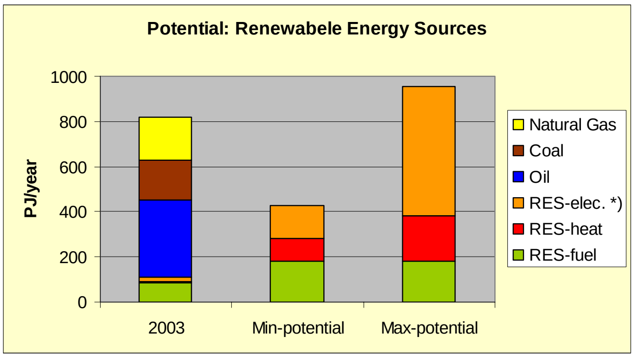

Fig. 3. Potential of RES in Denmark compared to the primary energy consumption in 2003

3. Reference scenario

Danish energy supply is traditionally based on the burning of fossil fuels. Denmark has very little hydro power potentials and during the 60ies and 70ies the electricity supply came solely from 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. Hence, by means of energy conservation and expansion of CHP and district heating Denmark has been able to maintain the same primary fuel consumption for a period of more than 30 years. Moreover 14 percent of fossil fuels have been replaced by renewable energy and even more by coal and natural gas, and consequently the Danish energy system has been changed from at situation in 1972, in which 92 percent out of a total of 833 PJ was oil, to a situation of today in which only 41 percent out of 828 PJ is oil. In the same period both transportation, electricity consumption as well as the area of heated space has increased substantially. Today the share of electricity production from CHP is as high as 50 percent, and approximately 20 percent of the electricity demand is supplied from wind power [21-26]. Figure 4 illustrates the development from 1972 until today and shows the expectations to the future in accordance with the reference scenario explained in the following.

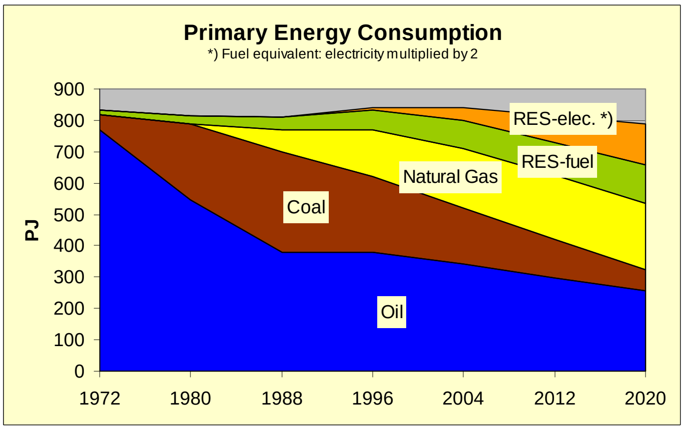

Fig. 4. Primary Energy Consumption in Denmark including expectations to the future.

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

One 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 the expected oil consumption.

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

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 percent of wind power and CHP in the Danish energy system [27]. As part of the work, Aalborg University made some long-termed year 2020 energy system analyses of investments in more flexible energy systems in Denmark [28]. These analyses were carried out on the EnergyPLAN energy system analysis computer model [29-31]. As 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 constituted by 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 per cent.
- 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 year 2020. The increase is primarily due to the implementation of one 150 MW off shore 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.

Table 2:
Reference energy system: Denmark year 2020

Key figure:	
Electricity demand	41,09 TWh/year
District heating demand	39,92 TWh/year
Excess electricity production	8,41 TWh/year
Primary Energy Supply	
Wind power	17,72 TWh/year
Fuel for CHP and power plants	92,29 TWh/year
Fuel for households	19,67 TWh/year
Fuel for industry	20,22 TWh/year
Fuel for transport	50,68 TWh/year
Fuel for refinery etc.	17,39 TWh/year
Total	217,96 TWh/year

In 2001 the expert group conducted the analyses separately on the western and the eastern parts of Denmark, which have separate electricity grids. For 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 is illustrated previously in figure 4 and the main figures are shown in table 2. A diagram of the energy flows in the system is given in figure 5.

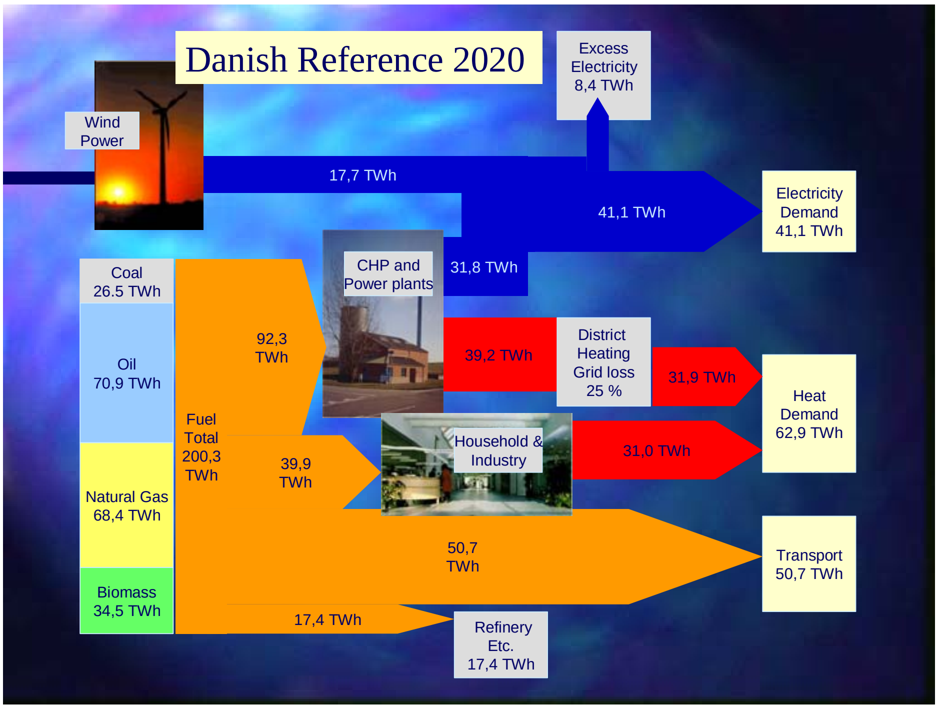

Fig. 5. Principle diagram of the energy flow in the Danish reference energy system year 2020.

4. Methodology

The aim of the analysis is to see if a 100 percent renewable energy system is a possibility for Denmark and hereby to identify key technological changes and suitable implementation strategies.

All changes have been carefully calculated on 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, limitation 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 [30,32-36].

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: 10 percent 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 defined as 50 percent electric output and 40 percent heat output of CHP plants. This can be achieved either by partial implementation of fuel-cell technology or by the improvements of existing steam-turbine/engine technologies. More CHP defined as a 50 percent of fuels for individual houses being converted to district heating and 50 percent of industry being replaced by CHP production.

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

All: A combination of all the three above measures

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 percent as well as replace more than 50 percent by CHP, etc. Still, such moderate technological changes fit well to illustrate the correlation between the different means.

4. 2 Flexible technologies

When increasing savings and 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 the Risø National Laboratory [37]. Vehicles that weigh less than two tons are transformed into a combination of battery vehicles and hydrogen fuel cell vehicles. In the scenario 20.83 TWh of oil is replaced by 7.3 TWh of electricity. Here the same ratio has been used to convert 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 a maximum capacity of 3500 MW.

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

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

The three measures and their technical designs are described in more detail in [35,38].

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 I figure 6 in terms of primary energy consumption.

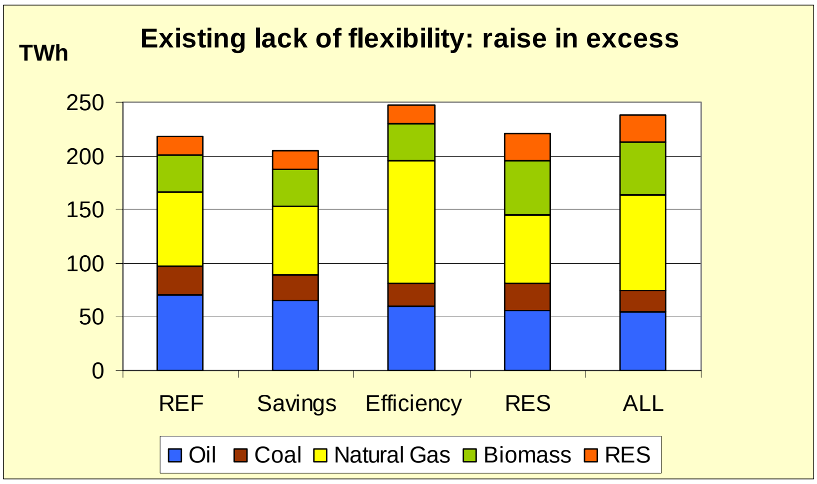

Fig. 6. Primary energy consumption with electricity excess production

As seen the tendency in the results is an increase in the fuel consumption rather than a decrease. This is due to 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 higher excess production unless something is done to prevent such problems. The resulting excess productions are given in table 3.

The general tendency is the more is done to decrease fossil fuels the more excess production.

Table 3
Resulting fuel consumption and electricity excess production

TWh/year	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

One way of avoiding the electricity excess 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 first CHP units are replaced by boilers, secondly boilers are replaced by electric heating, and thirdly the production from wind turbines and/or photo voltaic are simply reduced. This is a very simple and very cheap way of avoiding excess production, the results are show in figure 7.

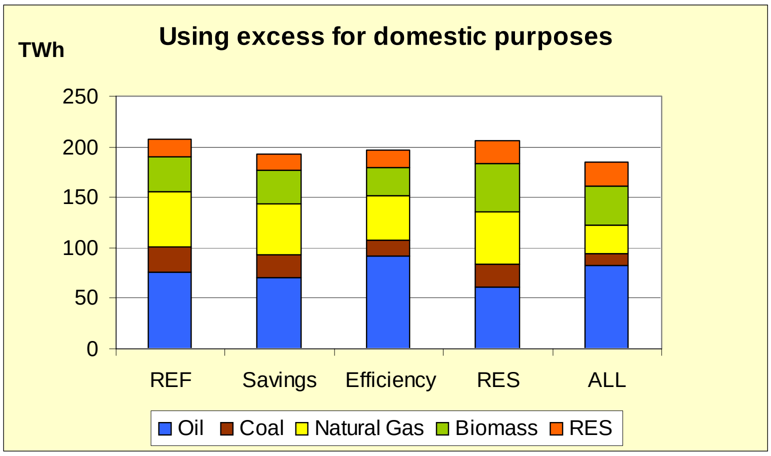

Fig. 7. Primary energy consumption without electricity excess production

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 from consuming oil into electricity as described in the previous section and shown in figure 8. In such case both the reference and all the alternatives have a decrease in fuel consumption.

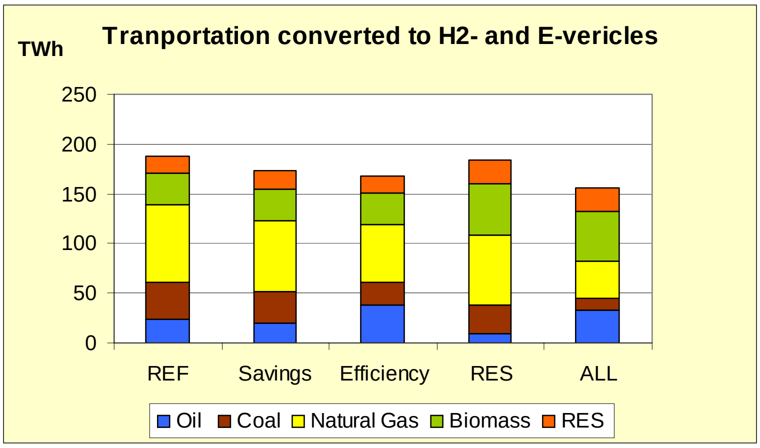

Fig. 8. Primary energy consumption when oil for transportation is replaced by electricity for electric vehicles and hydrogen vehicles.

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 have been combined with the other measures and finally wind power has been added to the system until the resulting fuel consumption has been equal to the available biomass resources of 180 PJ (50 TWh) per year. The results are given in figure 9.

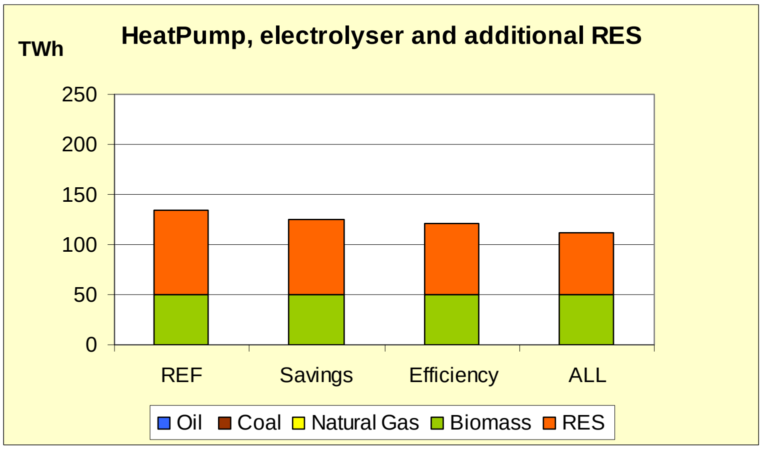

Fig. 9. Primary Energy Consumption when converting to 100 percent RES.

In this case it's all a matter of how much wind power is necessary in order to reach the objective. The resulting wind power capacity is given in table 4. As seen the Danish energy system can be converted into a 100 percent renewable energy system when combining 180 TJ/year of biomass with 5000 MW photo voltaic and between 15 and 27 GW of wind power.

Table 4
Resulting fuel consumption and needed wind capacity

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

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

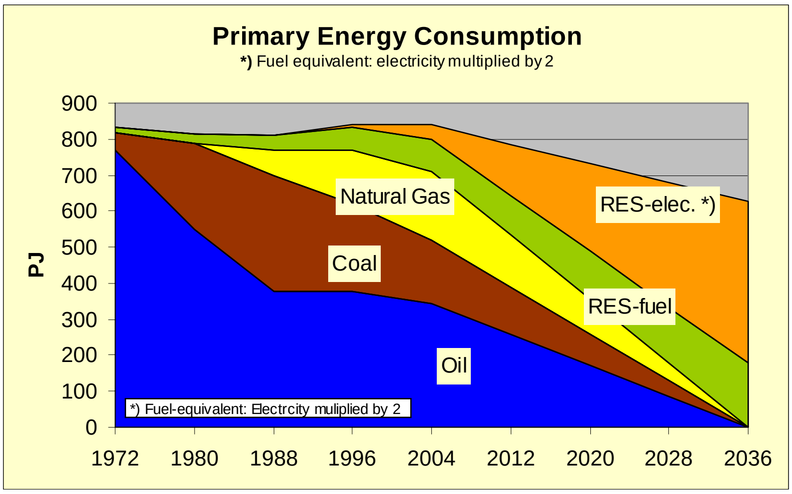

Fig. 10 Primary fuel consumption if Danish energy system is converted into 100 percent RES

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 per year. Here after the 15 GW can be maintained by continue to replace 500 MW each year. Since already 3 GW has been installed the total capacity can be reached within approximately 25 years, i.e. in year 2030.

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

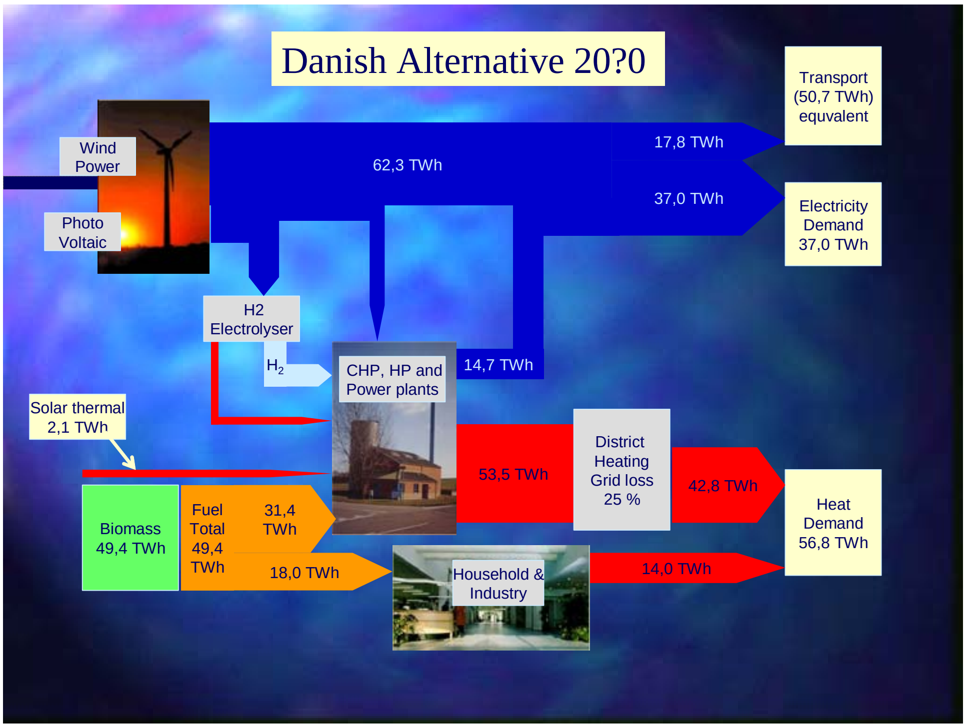

Fig 11: Principle diagram of the energy flow in a 100 percent Danish renewable energy system

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 of how to integrate the renewable sources in coherent energy systems influenced by energy savings and efficiency measures.

However, reaching a stage of 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 systems solutions. Such technological changes are required in order to bring about 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 percent renewable energy system.

The aim of the analysis is to see if a 100 percent renewable energy system is a possibility for Denmark and hereby to identify key technological changes and suitable implementation strategies.

All changes have been carefully calculated on 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, limitation in capacities of flexible technologies as well as demands for ancillary services.

The following improvements of system flexibility have been identified as being very important in order to convert the energy system into a 100 percent 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. Moreover, such technologies raise the potential of including wind power in the ancillary services of maintaining voltage and frequency in the electricity supply.

Next key technology is to include small CHP plants in the regulation as well as adding heat pumps to the system. Such technologies are of especial importance since they provide for the possibility of changing the ration between electricity and heat demand still maintaining the high fuel efficiency of CHP.

The third key technology is to add electrolysers to the system and at the same time make possible for wind turbines further to be included 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 percent renewable energy system when combining 180 TJ/year of biomass with 5000 MW photo voltaic 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 necessary capacity is almost only 15 GW.

15 GW wind power can be reached by installing 500 MW per year. Today Danish manufactories produce approximately 2000 MW wind power per year.

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