Fast Transition to Renewable Energy with Local Integration of Large-Scale Windpower in Denmark

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***Abstract*—The Danish Parliament has with overwhelming maqjority decided to change energy supply to renewable energy until 2050. Part of the Danish civil society, including the organizations SustainableEnergy and NOAH - Friends of the Earth Denmark, has proposed strategies and scenarios for fast transition to renewable energy until 2030. There are good reasons for this faster transition. One reason is the need to address climate change: some countries must lead the way, if the world should succeed in reducing global climate change to sustainable levels. In addition the Danish fossil fuel resources are fast depleting.**

In this paper SustainableEnergy is presenting analysis for this fast transition of Denmark until 2030, based on large-scale integration of windpower into the electricity grid, using varying demand and existing international electric interconnectors. In addition the scenarios include sustainable use of indigenous biomass. The analysis show balance between supply and demand in hourly time-steps until a situation with 100% renewable energy by 2030. By then windpower would provide 83% of the power and PV 7%. To compensate for the varying supply, proposed variable electricity demands are in 2030:

- **Electric-battery transportation, using 10% of power demand**
- **Heat pumps, mainly for district heating with large heat storages, using 16% of power demand**
- **Electrolysis to produce hydrogen for transport, using 14% of power demand**
- **Other flexible demand, using 8% of power demand.**

In addition the existing import and export via the existing interconectors to Norway and Denmark are used to increase flexibility in the system. The interconnectors to Germany are not expected to be useful for integration of windpower because of the large windpower capacity in Northern Germany with similar production profile as the Danish windpower.

An interesting observation is that the installation of large heat pumps for district heating are progressing with a speed that will reach the capacity expected in the scenario well before 2030. Electric vehicles and smart-grid systems are also progressing, but currently no fast enough to follow the proposed scenario.

In an accompanying economic analysis, the costs of this fast transition scenario is compared with a scenario for energy transition until 2050 presented by the official Danish Energy Agency, and a business as usual scenario. The economic analysis show that costs are similar. Under different conditions (high and low fossil fuel prices, high and low CO2-costs) the fast transition scenario will be respectively cheaper and more expensive that the less ambitious scenarios.

The work of SustainableEnergy also includes development of proposals to promote the transition to renewable energy until 2030: proposals for organisations, and the policies needed. This is based on on experiences of past increases of renewable energy, and incresed energy efficiency, as well as adopted plans for increase of energy efficiency. An innovative proposal is a tax on electricity that will vary hour by hour with wind and PV production with the lowest tax when the production is highest. That would effectively support the introduction of variable power demand.

The scenarios are analysed with Energy Plan for hourly energy balances and economic calculations, with preliminary, calculations made with LEAP using annual averages.

Keywords: fast transtion to renewable energy, large-scale integration of windpower, flexible demand, sustainable trasnport

INTRODUCTION

The Danish non-governmental organization SustainableEnergy (VedvarendeEnergi, previously Organi-sationen for Vedvarede Energi - OVE) has promoted renewable energy since it was formed in 1975. From early on in its work it cooperated with researchers to document how renewable energy could be utilized in Denmark, including integration of an increasing share of windpower. Researchers were already in the 1980's able to prove that 25% of the electricity could be produced by windpower without harming the stability of the electric grid [1].After the Danish Parliament in 1985 decided that nuclear power should not part of Danish energy planning and the release of the " Brundtand Report"[2] with its warning against global warming and other global problems, the Danish government started to plan for a future energy supply that would ultimately be supplied by renewable energy. In the first official Danish energy plan based on the principles of sustainability "Energi 2000"[3] is included a 15% reduction of primary energy use outside the transport sector , and a 20% reduction of CO_2 emissions, both until 2005, as well as a long-term illustrative scenario of reducing Danish CO_2 emissions by half.

In the following years researchers refined scenarios for a transition to 100% renewable energy, and in 1998 SustainableEnergy published a report with a scenario for a Danish transition to 100% renewable energy until 2030 [4], developed in cooperation with a number of researchers.

Following Danish successes in the 1990s with windpower, district heating, end-use efficiency in heat and electricity, and decentralized combined heat and power (CHP) plants, the transition almost came to a standstill when a liberal-conservative government came into office in Denmark in 2001. After a few years with the liberal-conservative government in power, it started to change course and the prime minister spoke for a Danish transition to renewable energy. Among others reasons for policy change was the depletion of Danish oil and gas resources. Forecasts were (and are) that Denmark will become net importer of these energy sources before 2020.

The government then established a temporary climate commission that in 2010 published its report with scenarios for transition to renewable energy[5] until 2050. One scenario had very large development of windpower, reaching 18,000 MW of installed capacity in 2050, equal to a 5-doubling from the then currrent level. Another scenario included large imports of biomass. Following the work of this commission, the government adopted the position that Denmark should change to a fossil free economy. Since nuclear power was not on the table, this in general meant a transition to renewable energy, but could also include Carbon Capture and Storage (CCS), another way of avoiding fossil fuel emissions.

In the meantime SustainableEnergy had pushed for a fast transition to renewable energy with reports published in 2005[6] and 2010[7] with scenarios and arguments for a fast transition to renewable energy until 2030. Also other organizations published scenarios and arguments for transition to renewable energy, including NOAH-Friends of the Earth Denmark that published its own scenario for a transition to renewable energy until 2030 [8]

With the new Danish social democratic government that came into power in 2011 new targets were set for the energy transition. The government set targets of 100% renewable energy in 2050 as well as interim targets of 50% windpower in the electricity mix by 2020, 40% reduction of greenhouse gases 1990 - 2020, and 100% renewable energy in the power and heat supply by 2035. The government also started negotiations in the parliament for realization of the targets. In 2012 the vast majority of the Parliament then made an agreement with targets of 100% renewable energy by 2050, 50% windpower in the electricity mix by 2020, and a number of actions to realize the targets. The former government parties joined the agreement and in this way it was made with exceptional high Parliamentarian support: more than 95% of the members of the Danish Parliament voted for it. Only a small, liberal, pro-nuclear party was against. Since 2012 some elements of the agreement have been re-negotiated and in July 2014 some previously agreed increases of energy taxes have been abolished. The targets are not changed, however.

With the 2012-agreement the Danish government started analysis on how to realize the transition to renewable energy and in March 2014 the Danish Energy Agency published a report with 4 scenarios for transition to renewable energy until 2050 with an interim target of 100% renewable energy in electricity and heating by 2035[9]. The four scenarios have different levels of windpower and biomass use. In this article the 2035 results of the most ambitious of the scenarios, combining windpower and hydrogen, is compared with a new energy transition scenario of SustainableEnergy.

In preparation of the discussions of 2030 energy targets, SustainableEnergy started a more in-depth study on how it would be possible to realize a faster transition to renewable energy than the government plans for 2050. Thanks to the support from the Velux Foundation it was possible to carry out larger analysis than previously, and involve more experts and others. This article describes the main results. As the work is still ongoing, more results are pending.

Fast Transition to Renewable Energy

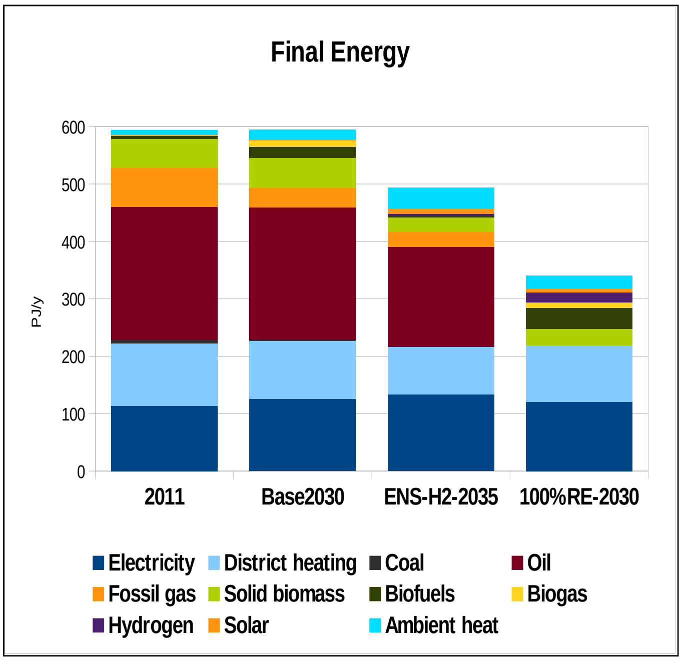
The aim of SustainableEnergy is a fast transition of the Danish energy system to 100% renewable energy, in a sustainable ways and using indigenous resources. Given the limitations of biomass resources, that can be harvested sustainably in Denmark, energy efficiency and the use of geophysical energy sources are key to realizing the aim. In addition the scenario includes limited growth, and in transport even a small reduction of the activity. For other sectors that transport the limited growth is in line with observed trends. The work with the scenario is divided in energy efficiency in buildings, energy efficiency in economic sectors of the society (productive sectors and service sectors), transport scenarios, change of energy supply for end-use sectors from fossil fuels to heat, electricity and biomass, increase of renewable energy supply, and integration of renewable energy sources in the energy supply system sources to meet demands.

Transition Sector by Sector

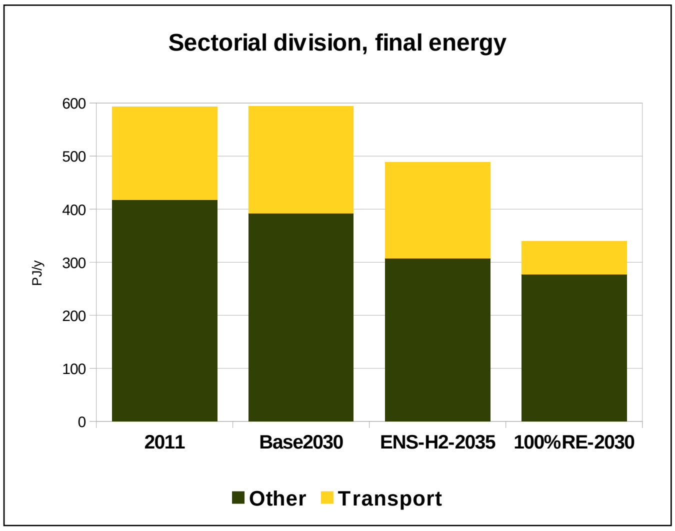
For the building sector the expected business as usual development includes heat and electricity use reductions because of increasing requirements to reduce heat demand and EU-requirements of electricity using products. The proposed scenario includes further reductions of heat demand with a faster rate of energy renovations in existing building and with a special emphasis on air-air heat exchangers in existing buildings. These extra energy efficiency activities are expected to deliver up to 30% reduction of heat demand in buildings (space heating and hot water). In the scenario 27% heat use reductions are included. These investments are relatively costly: 169 billion DKK to save 50 PJ, equal to 9.8 billion DKK/year with 4% interest and 30 year lifetime

For the production and service sectors an analysis in the project showed large potentials for energy efficiency with pay-back up to 10 years, but also that many of these energy efficiency measures were not carried out because of very high pay-back requirements, in particular in industry. Experience have shown that stable economic support and funding can make the companies realize energy efficiency measures with pay-back up to around 10 years. Thus these energy efficiency measures are included. They are somewhat cheaper than the measures in buildings: 24 billion DKK to save 27 PJ equal to 2 billion DKK/year with 15 year average lifetime and 4% interest rate.

For transport a scenario is developed with reduction of transport with emphasis on less commuting and better logistics to reduce freight transport. The scenario also include modal shifts from road to rail and change to electric cars and trains, combined with hydrogen in road transport. While the modal shift will require large investments in rail transport and road-rail combinations, the cost of inaction in the form of road expansions to reduce congestion will be equally expensive. Thus there are no extra investments expected with the transition compared with a basis scenario, where investments in motorways, road, and rail will exceed 200 billion DKK (27 billion €) in the period 2015-2030. In the transport scenario is also included a change of car ownership from individual ownership to car-sharing systems, where the car users can select the car most useful for each purpose. With such system fewer cars will be needed, and the vehicle cost will decrease. In addition electric cars are expected be become cheaper than petrol and diesel cars around 2020 in investment + operating and maintenance (O&M) and fuel costs, while hydrogen cars are expected to become cheaper than the fossil fuelled alternatives around 2025. In 2030 not all cars will be changed to electricity of hydrogen. The remaining fossil fuel cars will be fuelled with liquid biofuels. For the economic calculations no costs or savings are included for transport investments or vehicles. Only the fuel change appear and a smaller cost of 1 billion € for hydrogen filling stations.



Graph 1: Final Energy in 2011 and scenarios 2030/35



Graph 2: Final energy split in transport and other sectors

The change of energy supply shall also include change from oil and gas heating in the heating of buildings to district heating and heat pumps. While district heating is expected to cover 54% of het demand in the base scenario, it will cover 73% of heat demand in the 100% renewable energy /transition scenario in 2030 while the share of heat pump heating is expected to reach 22% in the transition scenario compared with only 11% in the base scenario. For production is also included a change from fossil fuels to solid biomass, heat pumps, and hydrogen while remaining gas use will be covered with biogas upgraded to natural gas quality with CO_2 removal. The costs of end-use energy transition for the production sectors is estimated at 10.5 billion DKK, equal to 0.94 billion DKK/year and the district heating is expected to cost 35 DKK/GJ of district heating delivered.

Final energy consumption in the scenario compared with consumption in 2011 and consumption in the Energy Agency Hydrogen scenario is illustrated in graph 1. The majority of the difference is because of the transport changes, a s illustrated in graph 2

The increase of renewable energy include:

- increase of windpower from presently 4000 MW (of which 3500 MW on land) and 5000 MW in 2020 to 13,000 MW in 2030, of which 5000 MW on land, 2500 MW near shore in the sea, and 5500 MW further offshore. Compared with other scenarios, this scenario has large emphasis on the land-based and near shore installations in the sea as these are cheaper, but also require more involvement of local communities

- Increase of solar PV from presently 500 MW to 4000 MW

- Increase of solar heating from presently 1 PJ to 12 PJ, of which 6 PJ in district heating and 6 PJ directly in households and service sector.

- Increase of geothermal heat from presently 0.2 PJ to 19 PJ. This will be installations for district heating with

2000-3000 m deep boreholes, mostly assisted with heat pumps.

- Increase of biogas production from currently 4.5 PJ to at least 17 PJ, using half of Danish manure as well as various organic waste and crop residues.

- Increase of straw use from currently 20 PJ to 53 PJ

- Use of 230.000 ha (9% of agricultural area) for energy plantation with permanent crops (such as permanent grass and willow) to produce 46 PJ of solid biomass, of which 10 PJ for production of fodder in bio-refineries to replace reduced grain production. The land for energy crops should be land with pollution problems because of leaching of nitrates and land with low yields because of depletion of topsoil.

- Other biomass production of 50 PJ from forests, waste wood, additional crops on existing fields, and other, smaller sources.

With the right combination, the increased use of Danish biomass will also reduce total greenhouse gas emissions from soil and manure.

For the energy conversion system is proposed a number of installations and measures that can balance the varying production of wind and solar energy:

- Heat pumps in district heating that can use wind and solar power when this is larger than normal demand, with a combined electric capacity of 1800 MW and a COP of 3, leading to a heating capacity of 5400 MW

- Heat storages 700 GWh in district heating, equal to one week of average heat demand, to store heat from heat pumps and CHP, and additional 900 GWh for solar heating as seasonal storages.

- Hydrogen production with an electric capacity of 2400 MW and hydrogen storages of 50 GWh

- Flexibility of 10% of normal power demand (8% of total power demand), half with flexibility over a day and half with flexibility over a week. In addition is included some flexibility in the charging of electric cars.

- Use of 1200 MW CHP and 3800 MW of peak power capacity to balance electricity production and demand. The peak power plants only operates 120 equivalent full load hours per year while the CHP operates.

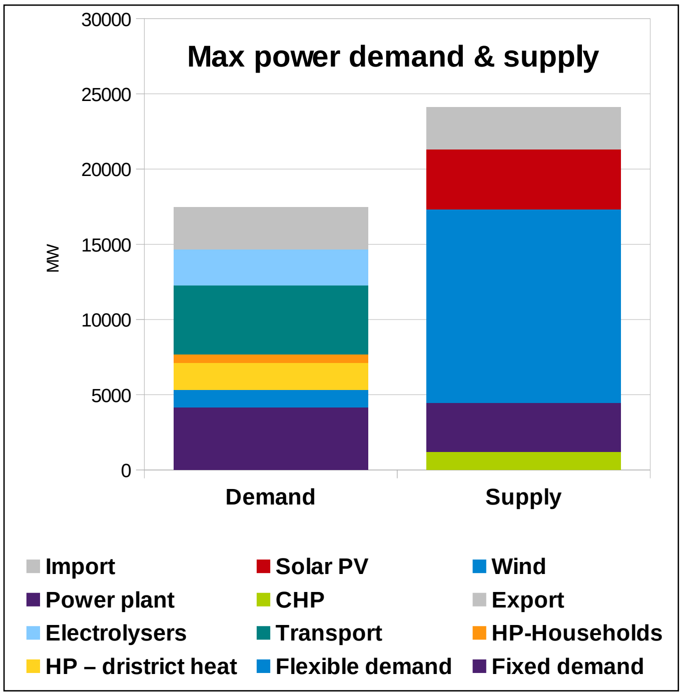
- Curtailing of windpower and production and up to half the solar power production to avoid excess production. In the current scenario 3% of windpower will be curtailed in 2030 ad no solar power.

- Use of existing underground gas storage to balance gas production and demand

- Use of existing 2800 MW interconnectors with Sweden and Norway on market conditions as part of Nordpool electricity market, while the Danish - German interconnectors are not used and no new interconnectors are included.

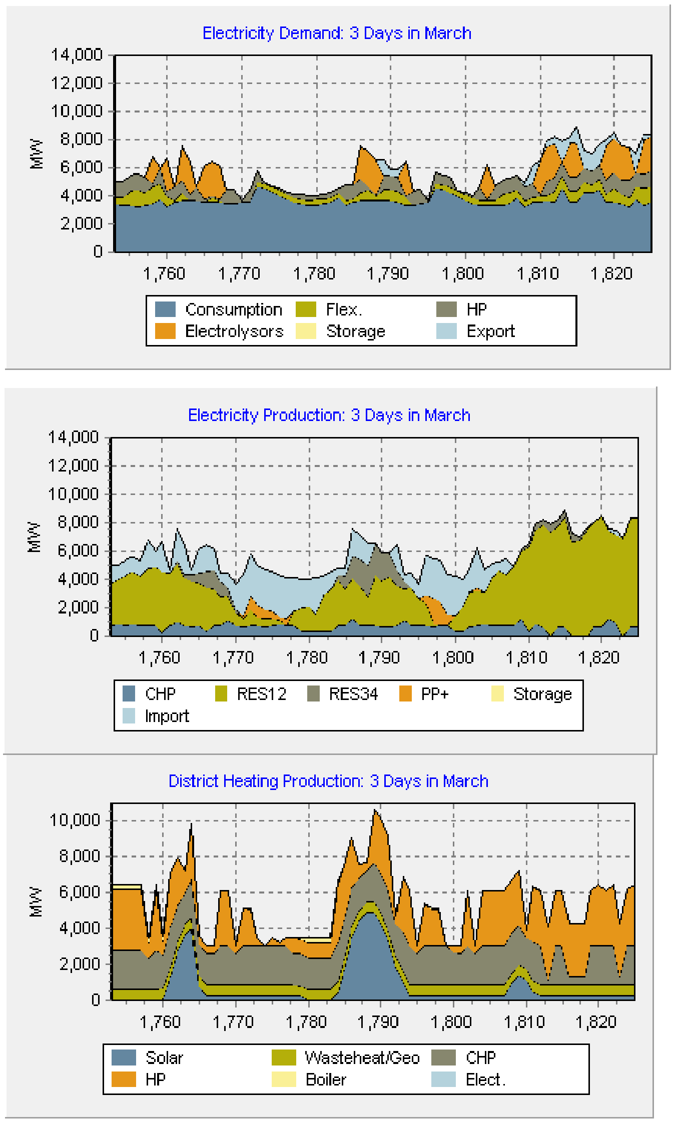
Fuel Balance(PJ/y)	Power & heat	Electro lysers	Bio Conversion	Trans port	Buil dings	Industry etc.	SUM
Gas	3.2	0.0	-13.9	0.0	0.0	10.3	-0.5
Biomass	43.7	0.0	66.9	0.0	6.1	21.6	138.3
Sun, wind, geo	196.5	0.0	0.0	0.0	0.0	0.0	196.5
H2	0.0	-17.0	0.0	13.5	0.0	3.5	0.0
Biofuel	0.0	0.0	-36.0	36.0	0.0	0.0	0.0
SUM	243.4	-17.0	17.0	49.5	6.1	35.4	334.4

Table 1. Fuel balance in 2030 with the 100% renewable energy scenario. 0.5 PJ gas is exported



Graph 3 Maximal power of demand and supply categories. All demands or all supplies will not be maximal at the same time, so the maximal power on the graph will never occur

This gives an energy system than can supply all Danish energy demand by 2030. The modeling with Energy Plan[10] shows that the system will be in balance every hour of the year.. An overview fuel balance is given in table 1, and electricity balance is illustrated in graph 3 while the hourly variations are illustrated with graph 4 with variations in supply and demand in 3 days in March. The days are chosen to illustrate both high-wind and low-wind hours. It shows how production is matched with flexible demand, heat pumps, electrolyzers and import/export. Also variation in the CHP production and power-only plants contribute to the electricity balance. The lowest graph illustrates district heating production and shows how the different heat sources combine, including solar heating and heating from CHP and heat pumps. The varying heat sources are supplying heat to heat storage tanks that in a cost-effective manner can smooth out the varying supply to a demand that is rather constant during the day (but varies from season to season).



Graph 4: Electricity production ("RES12" is wind, "RES34" is solar), electricity demand, and district heating ("wasteheat/Geo is only geothermal heat) in three days in March (hours no 1754-1824 of the year) in 2030 with the 100% renewable energy scenario and typical weather.

ECONOMY OF THE TRANSITION

The economy of a 100% renewable energy system is calculated using Energy Plan. With the same methodology is calculated the economy of a basis scenario with no additional measures after 2020, and the Danish Energy Agency's Hydrogen scenario" for 2035. The costs for energy supply and conversion technologies as well as for fuels are taken for Danish official forecasts [11][12][13] with a few exceptions:

- the future costs of solar PV is lower than the official forecast

- biomass costs are for 2020 instead of 2030 as the official figure for an increase in real costs of 12% in the period 2020 - 2030 is not well justified for a scenario where the production is national.

- costs for hydrogen storage and bio-refineries are own estimates as there is not official estimate for these technologies

In addition it has been necessary to interprete the official sources to calculate network costs of electricity and district heating networks. They cost used are 39 and 125 DKK/MWh respectively, representing pure network costs without administration etc. that is little dependent on use of networks. For all calculations has been used the official interest rate of 4% for evaluating energy investments and the officially expected CO_2 emission price for 2030 of 216 DDK/ton of CO_2 (29 $/ton of CO_2)

With these costs estimates and the above-mentioned costs for energy efficiency and transition in the end-use energy sectors, the economic evaluations show that the 100% renewable energy supply in 2030 will have annual costs of 66 billion DKK(9 bill. €), including energy efficiency costs, while the Danish Energy Agency's "Hydrogen scenario" has annual costs of 77 billion DKK (10 bill. €) and the base scenario has annual costs of 90 billion DKK(12 bill. €). The cost structure is very different between the base scenario and the 100% renewable energy supply scenario, with large fuel costs in the base scenario and large investments in the 100% renewable energy scenario. In this way the base scenario's costs are strongly dependant on the fuel costs while the 100% renewable energy scenario's costs are strongly dependant on interest rates. The cost structures of the three scenarios are illustrated in graph 4

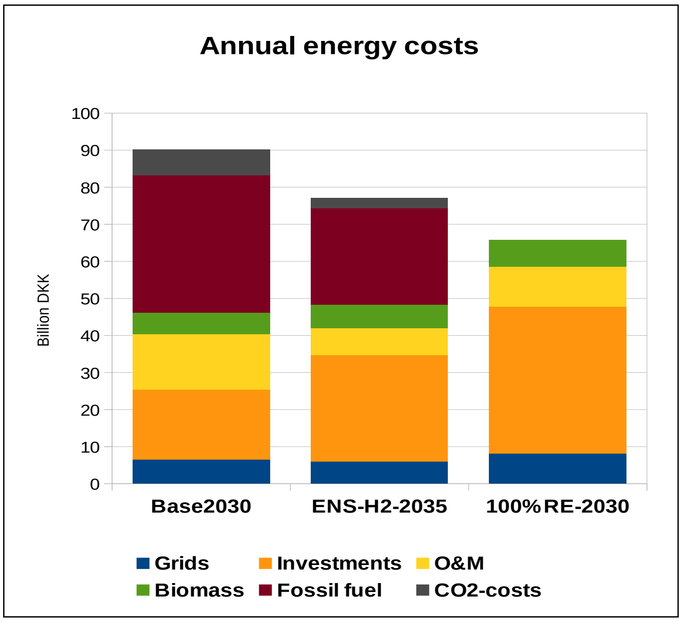
The result of the economic calculations show that the 100% renewable energy scenario has the lowest costs. This has a number of reasons of which the three most important are that the transition of the transport system is estimated to have minimal costs as explained above, that the interest used of 4% is low than the rate used by many decision-makers, and that for technology costs are used future costs, which generally are lower than today's costs with technology learning

PROPOSALS TO REALIZE THE TRANSITION

A fast transition to renewable energy will require continued, concerted actions in all sectors. The main measures proposed by SustainableEnergy are briefly presented here.

To reduce energy consumption in buildings is proposed, in addition to ongoing measures, an increased emphasis on energy renovations with increased free advice, regular energy audits, a subsidy system similar to a present Swedish scheme, and stronger enforcement of the requirement to carry out energy renovation when houses are renovated. For change of heating from oil and gas is proposed strategic energy planning to determine which areas should have district heating as well as loan guarantees for the conversion of houses in the areas of Denmark, where it is hard to get mortgage loans.

For energy efficiency and conversion to renewable energy in the productive sectors is proposed, in addition to existing promotion programs, to introduce loan guarantees to enable companies to obtain low-interest loans as well as transition agreements with companies, where they will plan for transition to renewable energy until 2050.



Graph 4 Division of annual costs in major categories for the three scenarios

For the transport is proposed that transport investments in the order for 200 billion DKK, or 10-15 billion DKK annually, are used for development of trains and lines, bi-cycle facilities, and intermodal changes. While about 1/3 of this budget is already allocated to develop Danish trains and lines, it will require re-allocation of the remaining 2/3 of the state transport investments that are currently allocated to highways. The transition to electric and hydrogen cars should be promoted by lower taxes on electric and hydrogen cars, and tax exemptions when they are used in car-sharing arrangements. The reductions in transport should be promoted by phase-out of subsidies for commuting and road-pricing on road freight, similar to the Germany system. These transport measures should be combined with increased car taxation.

For the development of renewable energy is proposed continued feed-in tariffs on gradually lower levels, with guaranteed prices for about 10 years for windpower and solar PV, and longer for biogas plants. For development of energy crops, increased straw use and other biomass, is proposed long-term purchasing agreements with stable price between farmers and CHP plants and bio-refineries. Sustainability criteria for the biomass production should be included, including criteria to increase greenhouse gas reductions.

To promote the flexible energy system and flexible electricity use, the main proposal is that electricity taxes and tariffs for transmission and distribution are made dynamic so they vary hour by hour with the production of wind and solar power. When renewable production is higher than demand, tax and tariffs should be at a minimum while they should gradually increase with reducing share of these renewables in the electricity mix. With regular adjustment of formulas for tax and tariffs the revenues for state and power companies can be kept at a stable level.

Public participation and support is crucial for the fast transition. In addition to above specific measures for promotion of energy efficiency and renewable energy, is proposed a development with emphasis on public participation. This includes local involvement and ownership or co-ownership of investments in windpower, solar, and biogas plants; consumer ownership of district heating; focus on involvement of owners and renters of houses in energy renovations, and increased involvement of citizens in transport planning and organization.

Finally the transition should be assisted by research, development and demonstration. While most proposals are based on well-known technologies and policies, further development and demonstrations are needed of for instance bio-refineries and use of hydrogen in production and heavy transport. Also further demonstration is needed of combined heating solutions with many heat sources and heat storages for district heating, as well as in social innovation to increase popular involvement.

Documentation of scneario and policy proposals is available in Danish online [14]

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