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The Role of Nuclear Power in the Future Energy System

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Abstract

Currently widely accepted consensus is that greenhouse gas emissions produced by the mankind have to be reduced in order to avoid further global warming. The European Union has set a variety of CO_2 reduction and renewable generation targets for its member states. Nuclear power is a low carbon energy technology and it seems to have many attractive properties in regards to carbon free energy system aspirations. The study presented in this paper is condensed version of a Master's thesis [1]. In this study, the role of nuclear power in the future Nordic energy system is the main research question. The basic characteristics and properties of nuclear power are presented in the study. Also other selected carbon free energy production methods are presented, as well as energy storages. Carbon free energy system in Nordic region is modelled with different scenarios. The model is used to analyse whether the constructed energy system consisting only renewable and nuclear generation can function. This paper summarizes the aforementioned study and presents the main results.

Keywords:	Nordic energy system; Energy system model, Nuclear power

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1. Introduction

Climate change mitigation has emerged as one of the most popular and important targets for mankind. Widely accepted consensus is that greenhouse gas emissions have to be reduced to avoid, or even halt, further global warming. The energy sector has an important role in reducing these emissions, especially carbon dioxide emissions.

Globally, fossil fuels dominate the energy sector and they are likely to do so in the foreseeable future. Emerging economies, such as China and India, are unlikely to abandon fossil fuelled energy generation anytime soon. In more advanced economies, a transition to different low carbon technologies, such as renewables, is being encouraged and even demanded.

The energy system in the Nordic countries is already one of the most carbon free in the world [2]. The majority of the CO_2 emissions in the Nordic power sector come from coal, peat and natural gas power plants in Finland and Denmark. Finland generated around 46% and Denmark 33% of the 67 million tonnes of CO_2 that the Nordic power sector generated in 2010 [2]. The overall share of renewables, mainly hydropower, in Nordic power generation was around 60% in 2010. According to various IEA scenarios, the share of renewables in Nordic power generation will increase to 80% by 2050. In this study, the Nordic energy sector is assumed to be carbon free by 2050 and this is achieved with using nuclear power together with a large share of renewables [1].

Nuclear power is the world's second-largest source of low carbon electricity after hydropower and in OECD countries it is the largest source of low carbon electricity [3]. It is important to consider the role of nuclear power in the future carbon free energy system.

The model in this study calculates generation mixes, produced and consumed total energies and hourly energy balances in the Nordic energy system. Electricity prices, market mechanisms or detailed production and construction costs of the generation fleet are not considered. Rudimentary cost comparisons between different generation technologies are performed but these are only indicative as the aforementioned financial aspects are not in the scope of this study. The different scenarios presented are not forecasts, rather they present alternative targets and avenues for a carbon free energy system. Generation mixes used in the thesis are either based on the literature or they are chosen somewhat arbitrarily to construct and study different carbon free energy systems. Future scenarios are set for the year 2050 following the various IEA scenarios and targets found in the Nordic Energy Technology Perspectives 2014 [2].

2. Basic characteristics of nuclear power

In regards to carbon free energy system aspirations, nuclear power seems to have many attractive properties. The basic characteristics and properties of nuclear power are presented more widely in the study and include e.g. current and future reactor technologies, resources and resource efficiency, emissions, and flexibility of nuclear power plants [1]. The impact of nuclear power to energy security and security of supply is presented below.

2.1. Energy security and security of energy supply

It is clear that security of energy supply and the continuous availability of energy at an affordable price is invaluable for society. It not only provides essential services for production, communication and trade but is also invaluable in maintaining basic human needs such as heating, ventilation and food and water supply. Historically the introduction of nuclear power to the country's electricity generation mix has improved the energy security of that country. This can be seen, for example, in the evolution of the generalized Simplified Supply and Demand Index (SSDI) which indicates the security of supply for a defined region. Figure 1 shows the SSDI values in selected OECD countries from 1970 to 2006.

For example, the United Kingdom's switch from coal to gas and the introduction of nuclear programmes in Finland, France, Sweden and the United States improve the value of the SSDI [4]. Generally, the country's security of energy supply and energy security improve with the introduction of nuclear power and decreases often relate to increases in imports.

Security of energy supply and energy security can be divided into external and internal dimensions, seen in Figure 2. Nuclear power has several characteristics which improve the energy security of a certain nation, especially regarding the external dimension.

Few examples as how the nuclear power can improve the energy security are its positive attributes in following categories: geopolitical risk, safety and adequacy of international infrastructures, price stability and operational reliability. Uranium resources are available from diverse sources, both geographically and politically, which in turn lessens the geopolitical risk of acquiring nuclear fuel or uranium [5]. Global nuclear fuel supply chain has yet to experience a serious disruption and nuclear power involves long lead times allowing the nuclear industry to have ample time to anticipate and respond to changes in uranium demand. Generating costs for nuclear are less sensitive to changes in fuel costs than those of fossil fuelled generation and nuclear power can increase the price stability in the region. Nuclear power plants also traditionally have high capacity factors which suggests good operational reliability [3].

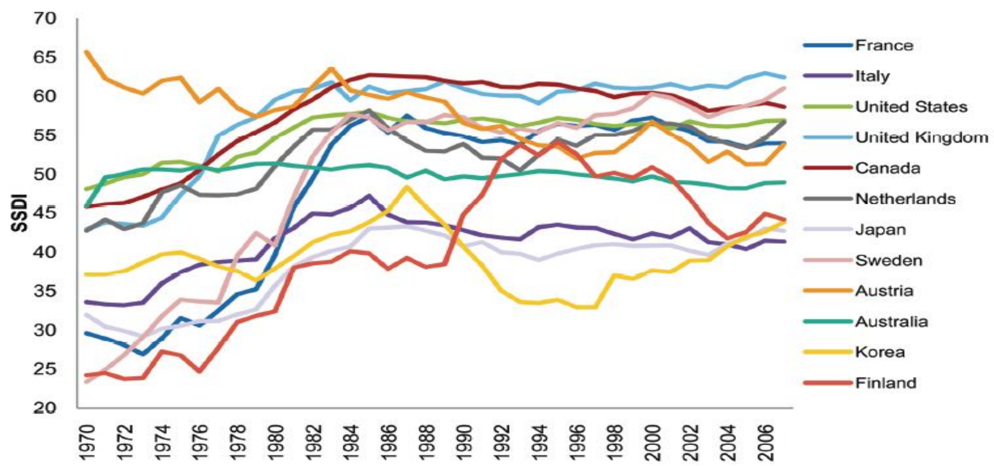

Figure 1: The evolution of the SSDI in selected OECD countries [4]

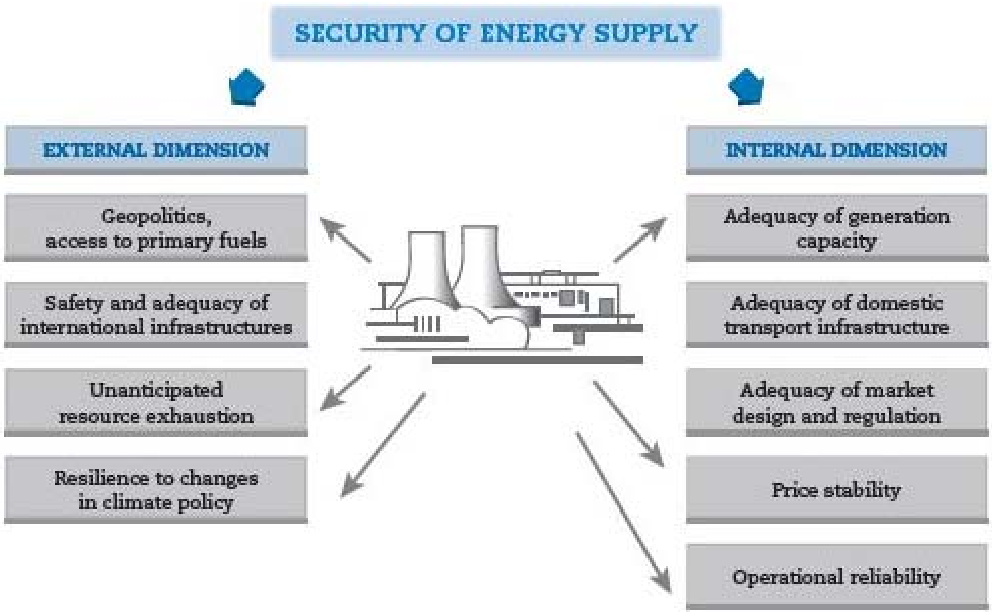

Figure 2. Dimensions of energy supply security [4]

3. Energy system model

Globally, the current energy system is based on large, centralised generation using mainly fossil fuels. The future low carbon energy system will have greater diversity of technologies and fuels, and especially more renewables will be used. In addition to renewables, nuclear power could be a major contributor to the decarbonisation of the electricity supply.

Renewable energy output has a tendency to fluctuate depending on the weather. Today's energy systems uses mainly hydropower and fossil fuelled power plants as regulating power to stabilise the power grid and to meet the supply and demand challenges. In this study, a future energy system is envisaged to be carbon free and thus, the share of fossil fuel dependent energy generation is significantly lower, or zero, in the system. Decarbonising the energy system requires alternative grid stabilising methods and technologies. Increased volumes of variable production from wind and solar will highlight issues related to regulating power. In Nordic countries, the large share of hydropower will help the transition and will become increasingly valuable in regulating electricity systems in these countries and Northern Europe in general [2].

The Nordic countries have set their ambitions and energy targets on a Carbon-Neutral Scenario (CNS), in which CO_2 emissions in the region are reduced by 85% by 2050 compared to emission levels in 1990. Within this strategy, some Nordic countries would achieve a carbon-neutral energy system by 2050 [2].

The future energy system in the Nordic countries in 2050 is studied and analysed by constructing a basic model representing the energy system in the Nordic countries [1]. The model uses real 2013 Nordic load data from Nord Pool Spot which is then scaled up to estimated 2050 consumption levels [6]. The IEA estimates that Nordic countries will have a load between 430 and 450 TWh in 2050 and that Nordic countries will become net exporters of electricity [2]. Every hour of the year has a load value, i.e. how much electricity was consumed in any given hour in the Nordic countries in 2013. The load demand is then satisfied with different types of electricity generation in a particular order.

In this study, the energy system has electricity generation from the following sources: hydropower, wind power, nuclear power and biomass fuelled generation. The Nordic grid connections between Denmark, Finland, Norway and Sweden are considered to be more than adequate in 2050, meaning that Nordic countries and their electricity grid is considered as a single unit. International grid connections, possible heat storage and the geographic distribution of wind generation are not directly analysed in the model. In all future scenarios, both the IEA's and the ones analysed in the model, growth in electricity generation outpaces electricity demand in the Nordic countries, implying a rise in the net exports from the Nordic region.

The model logic is shown in Figure 3. The generation mix, capacities and shares for different generation sources vary depending on scenario.

The generation mix used in the model is based on the IEA's scenarios found in their publication Nordic Energy Technology Perspectives 2013 (NETP) but with little modifications [2]. The Base scenario, discussed in chapter 3.1, in the model is based on IEA's Carbon-

Neutral Scenario (CNS) found in the NETP. The CNS scenario still has some fossil fuelled generation, opposed to none in the model, and about 2 GW of solar capacity. According to the IEA, solar generation is not significant in Nordic countries in 2050. This may prove to be wrong, but one purpose of the model was to consider whether system consisting of large amount of intermittent renewable generation, traditional renewable generation and nuclear can function. In the model, wind power represents intermittent renewable generation and solar generation is not modelled.

Hourly output data in 2013 for the Nordic wind power was extracted from various sources. This allows to use realistic wind profile in the model. Hourly installed capacities and peak load hours were calculated and modified for the year 2050 in order to take into account better windmills and turbines, larger wind farms and the possibly larger share of offshore wind power. Nordic wind power has 3 265 peak load hours in the model.

Nordic electricity generation is currently dominated by hydropower and hydropower will also be the largest generation source in 2050. In the model, a portion of the total hydroelectric power capacity is dispatchable and the remaining portion non-dispatchable. Some of the Nordic hydropower plants are run-of-river plants with limited water basins and these types of hydropower plants have limited manoeuvring and adjusting capabilities. According to the NETP, around 35 GW of the 60 GW of hydropower capacity in the Nordic countries in 2050 could be considered dispatchable [2]. Dispatchable hydropower is the flexible element in the model and it responds to the possible electricity deficits with no other limitations than the maximum capacity it has. The non-dispatchable portion of the hydroelectric power produces electricity evenly over the year.

At the time of writing, only Finland and Sweden of the Nordic countries have nuclear generation; 2.7 GW and 9.5 GW respectively. However, the two majority

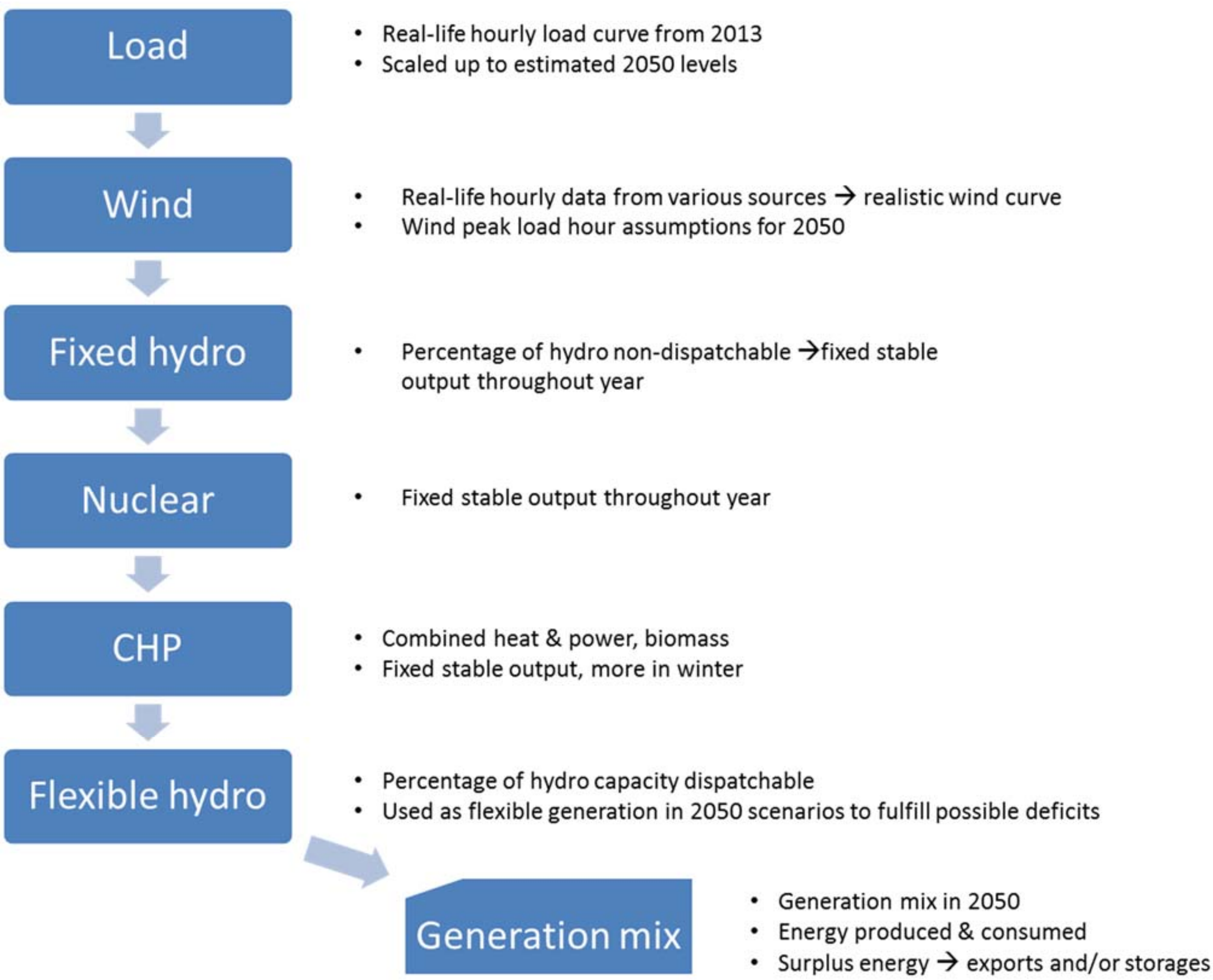

Figure 3. Illustration of model logic [1]

operators of nuclear power plants Ringhals and Oskarshamn in Sweden have announced intentions to close down some production capacity. The projected loss of capacity (around 3 GW) is not considered in this study. It is unlikely that Norway or Denmark will build nuclear power generation in the future. The IEA estimates in the Nordic Energy Technology Perspectives that the capacity for nuclear generation in Sweden will remain the same in 2050 as it is at the time of writing but they anticipate that Finland's nuclear generating capacity will rise from the current level to 6.4 GW [2]. These same assumptions are used in the Base scenario of this study, meaning that in 2050 Nordic nuclear generating capacity is estimated to be 15.9 GW.

In the model, all the Combined Heat and Power (CHP) generation is estimated to be biomass fuelled in 2050. Fossil fuelled CHP is non-existent in 2050. Combined Heat and Power generation is assumed to follow the heat demand in the Nordic countries and is not flexible in the model. CHP plants feeding different industries are assumed to run evenly throughout the year while district heating is used mainly only in the winter months. Therefore, it is assumed that CHP produces double the amount of energy in winter compared to summer.

The model basically shows hourly energy balances and system is considered to function properly when there are no deficit hours present. Simply put, the energy system in the model has to produce more energy than it consumes. All the balancing needs in the Nordic scenarios are handled with hydro power.

3.1. Base scenario

In this Base scenario (year 2050), the Nordic energy system has about 76 % renewable generation and 24 % nuclear and the whole system is carbon free. The only intermittent element in the system is the large share of wind power. A portion of hydropower is considered non-dispatchable and acts as a base load power source in the system. The total energy of the nuclear power is divided evenly throughout the year reflecting its role as a base load power source in the energy system. There is, however, the possibility to use nuclear power as a flexible power source, but this is not analysed in the Base scenario. CHP is assumed to generate 100% more energy in winter months (November to April) than in summer months and the output is stable. The energy generated by CHP in the model is electricity; heat energy or heat flows in the energy system are not included in the model. Fixed hydropower, nuclear power and biomass based CHP all generate electricity evenly throughout the year. Finally, the remaining hydropower is dispatchable and is the only flexible form of power generation in the Base scenario [1].

The overall electricity generation increases by 30% compared to 2013 levels, from 384 TWh to 506 TWh and the generating capacity with about 30 GW. These values are on the same scale as presented in the NETP. In the Base scenario, the constructed energy system has a generation surplus of 76 TWh. The IEA estimates that, depending on scenario, the Nordic countries will have a combined electricity exports between 40 TWh and 100 TWh [2].

In Europe, intermittent wind and solar power are becoming more popular and it is intended that fossil fuelled power generation will be abandoned in many countries, thus the need for regulating power capacity will increase. The large hydropower capacity in the Nordic system is valuable and can help to regulate the electricity systems in Northern and Central Europe.

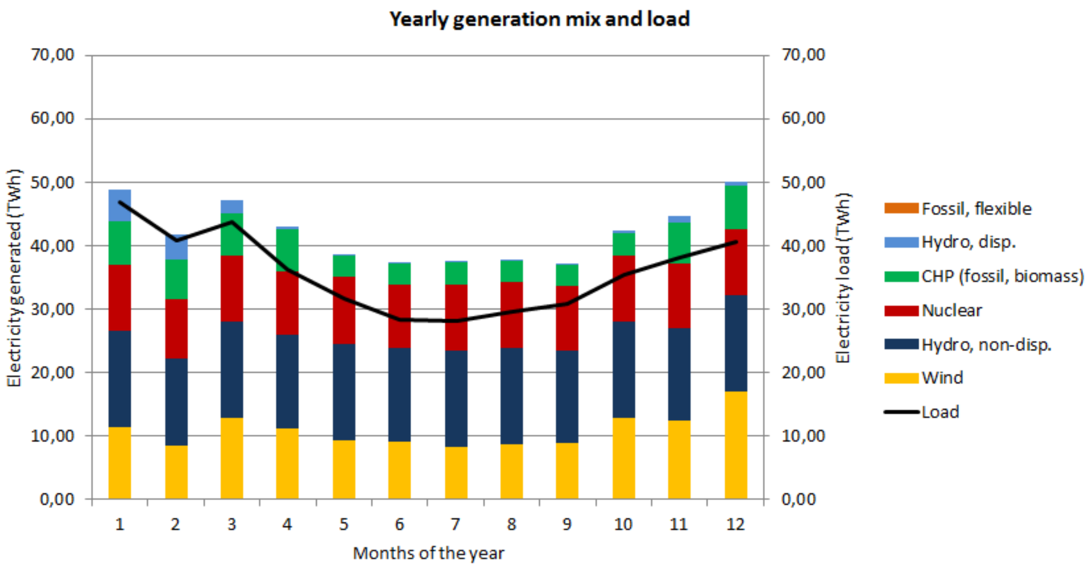

Figure 4: The generation and load month to month in the Base scenario [1]

The monthly generation profile for the Base scenario is presented in Figure 4. The black line represents the load in Nordic countries. The different electricity generation sources are, from bottom to top, in the same order as in the model [1].

As can be seen from the figure, wind generation and dispatchable hydropower are the only intermittent electricity generation sources. Non-dispatchable hydro, nuclear and CHP generation have no hourly variation. Nuclear generation, non-dispatchable hydro and biomass CHP provide the base load generation to the energy system. The Nordic countries have more load in the winter months and therefore dispatchable hydropower is needed to compensate for deficits. Overall, the energy system constructed in the Base model has no deficit hours over the whole year, meaning that there is always at least the same amount of electricity generation as there is consumption.

Some specific situations were also analysed by modifying the Base scenario. Modifying the levels of wind generation allows to see whether the energy system can handle low wind hours. Zero wind situation is unrealistic but shows that remaining generation sources in the Base scenario can generate enough electricity to satisfy the demand. This situation highlights the role of different electricity sources in the system. This also highlight the importance of having versatile generation mix. Dispatchable hydropower is used when needed while nuclear power provides reliable and stable electricity regardless of weather conditions. Nordic hydropower generation is also somewhat affected by the water levels.

The Base scenario was also modified by replacing 15.9 GW of nuclear power with either more wind power, biomass fuelled generation or combination of these two generation sources. Aim was to generate as much energy in the system as in the non-modified Base scenario. In order to do so without nuclear, a total of 73 GW of wind power capacity was needed, 33 GW more than in the Base scenario. For biomass fuelled generation, 25 GW of additional biomass fuelled capacity would be needed to replace nuclear generation. This would bring the biomass fuelled generating capacity to 37 GW and the strain on the biomass production and fuel transportation system would be greatly increased.

3.2. Low hydro scenario

The energy system in this scenario is not strictly based on any real life country, region or any IEA scenario. However, as the model uses real data for the Nordic electricity load also this scenario uses the Nordic load pattern [1]. This means that the largest loads are in the winter months. This scenario is an illustration of a situation with limited hydro power resources and thus, is not relevant in Nordic energy system.

The purpose of this scenario was to construct a carbon free energy system in 2050 without a large amount of hydropower to see if a system containing only wind, biomass and nuclear power together with energy storage can form a working energy system and to see whether hourly balancing can be achieved with other elements of the system. If the energy system has large amount of hydropower capacity, the challenges that arise from large shares of intermittent renewable generation, such as wind and solar, are more easily mitigated.

The Nordic energy system has significant amounts of hydropower generation available and it has the largest impact on the Nordic energy system. In this scenario, the share of hydropower compared to other generation sources is insignificant. The Low Hydro scenario includes electricity generation from wind, nuclear and biomass. Hourly balancing and flexibility is ensured by incorporating energy storage into the energy system. The shares and capacities for different generation sources and storage are selected in such a way that there are no deficits in the system after energy storage.

Wind, nuclear and biomass capacity values were chosen in such a way that the system generates around the same

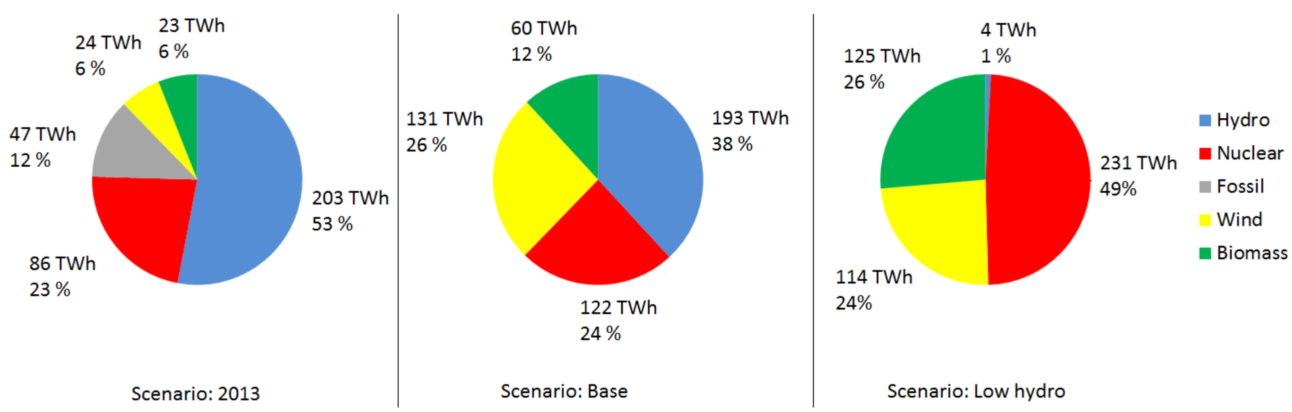

Figure 5: Electricity generation mixes. Energy storage not included [1]

Table 1: Capital cost and O&M costs of different technologies [7]

Technology	Nominal capacity [kW]	Capital cost [$/kW]	Fixed O&M [$/kW-yr]	Variable O&M [$/MWh]
Advanced nuclear	2 234 000	5 530	93.28	2.14
Wind, onshore	100 000	2 213	39.55	0
Wind, offshore	400 000	6 230	74.00	0
Biomass, BFB	50 000	4 114	105.63	5.26
Biomass, CC	20 000	8 180	356.07	17.49

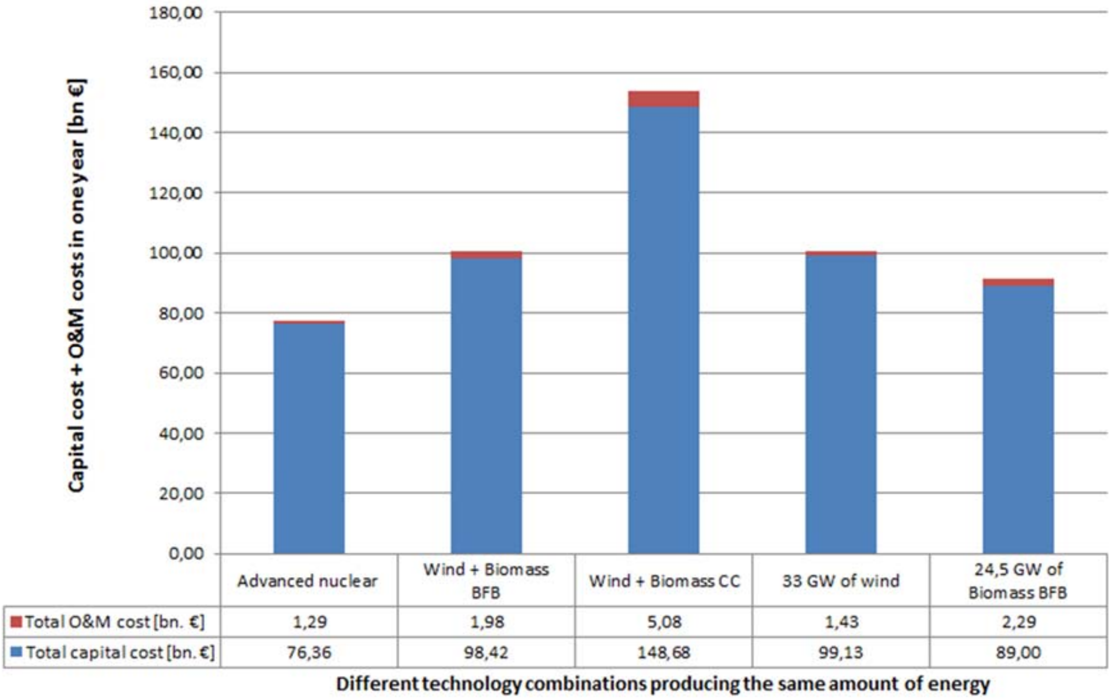

Figure 6: Total capital cost and O&M costs in one year for different technology combinations. Here 1$ = 0.833€

amount of electricity as the IEA estimated in the Nordic Energy Technology Perspectives [2]. If the energy system had surplus energy in any given hour that energy was stored in long and short term storage facilities. Energy stored in these facilities was utilized in the hours when electricity generation from wind, nuclear and biomass was not enough to satisfy the demand. The constructed energy system has no deficit hours during the year and shows that a carbon free energy system can function without hydropower. Figure 5 presents electricity generation mixes in 2013 and in the Base and Low hydro scenarios.

Nuclear energy has an important role in this system as it produces almost 49% of the total energy while its generating capacity is 33% of the total capacity connected to the grid. Replacing this much nuclear energy with other low carbon technologies would require significant investments not just in generating capacity but also in technologies involved in balancing the grid. For example, solar and wind power do not introduce rotating inertia naturally to the grid while nuclear power does. Power grid inertia is one parameter the synchronized operation of the grid is based on and it determines the immediate frequency response. If the overall inertia in the power grid is low, the grid frequency reacts nervously to sudden changes in generation and load patterns. To put it simply, inertia is the grid's resistance to change [1].

Basically all thermal power plants, whether they are fossil, nuclear or biomass fuelled, introduce rotating inertia to the power grid as their synchronous machines, generators and turbines, are connected to the grid directly. This rotating inertia is essential as it helps balancing the grid.

3.3. Cost comparison

Financial considerations were not the main focus of this study but some comparisons were made. Table 1 gathers capital cost and operation & maintenance costs of different technologies with a certain nominal capacity.

The information in Table 1 is used to calculate the total capital cost and O&M costs in one year for different technology combinations. These combinations produce the same amount of energy. The amount of energy selected for this comparison is the amount that seven nuclear power plants (total of 15.6 GW) from Table 1 produce over the year. This is about the same as in the Base scenario (15.9 GW of nuclear power). Figure 6 shows these costs.

The second and third columns have 15 GW of wind and 14 GW of biomass power. Each column produces the same amount of energy and Figure 6 shows how much it would roughly cost to replace 15.6 GW of nuclear power with alternative low carbon technologies. This is just a rudimentary comparison as financing, interests and market mechanisms are not considered. Still, it shows that nuclear power is cost effective option when comparing purely total capital costs and operation & maintenance costs.

4. Conclusions

All the scenarios constructed in the model have working energy systems where there are no deficits after all the different elements of the systems have made their contributions. A broad general conclusion from the analyzed scenarios is that nuclear power provides stable energy generation for the system without direct greenhouse gas emissions. Nuclear power generally has high capacity factors and peak load hours and its high stable electricity output helps to offset the intermittent profile of wind power.

Nuclear power offers grid management services which traditionally are not offered by wind or solar power. These include primary and secondary frequency control, predictable and controllable availability and rotating inertia. All of these are needed in order to have a functioning energy system making an energy system with 100% share of renewables hard to realise. As of now, these grid management services are performed by fossil fuelled generation, nuclear generation and hydropower. The Nordic countries are in the fortunate position that they can utilize the vast hydropower capacity of Norway. Hydropower is an excellent form of power generation for regulating power and for grid balancing purposes, but there is natural limit for hydropower capacity. As future energy systems abandon the use of fossil fuelled generation, nuclear power can replace it as a low carbon technology while maintaining grid stability.

The model and scenarios in this study show that it is possible to form a functioning, 100% carbon neutral energy system by combining greenhouse gas free renewables and nuclear energy. Wind power has large share of the total produced energy, but its generation profile fluctuates. Production from wind turbines is highly dependent on the prevailing weather conditions. Nuclear power produces electricity evenly and predictably throughout the year. Biomass fuelled CHP also produces electricity and heat evenly throughout the year. Their roles are equally as important as hydropower is; however wind and hydropower capacities cannot satisfy the consumption demand by themselves. Out of these generation sources, nuclear power produces the most energy per installed capacity.

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