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Research article

Energy security impacts of a severe drought on the future Finnish energy system

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ABSTRACT

Finland updated its Energy and Climate Strategy in late 2016 with the aim of increasing the share of renewable energy sources, increasing energy self-sufficiency and reducing greenhouse gas emissions. Concurrently, the issue of generation adequacy has grown more topical, especially since the record-high demand peak in Finland in January 2016. This paper analyses the Finnish energy system in years 2020 and 2030 by using the EnergyPLAN simulation tool to model whether different energy policy scenarios result in a plausible generation inadequacy. Moreover, as the Nordic energy system is so heavily dependent on hydropower production, we model and analyse the impacts of a severe drought on the Finnish energy system. We simulate hydropower availability according to the weather of the worst drought of the last century (in 1939–1942) with Finnish Environment Institute's Watershed Simulation and Forecasting System and we analyse the indirect impacts via reduced availability of electricity imports based on recent realised dry periods. Moreover, we analyse the environmental impacts of hydropower production during the drought and peak demand period and the impacts of climate change on generation adequacy in Finland. The results show that the scenarios of the new Energy and Climate Strategy result in an improved generation adequacy comparing to the current situation. However, a severe drought similar to that experienced in 1940s could cause a serious energy security threat.

1. Introduction

Energy security is a multidimensional and evolving concept. Moreover, it is increasingly popular as a research subject. A large body of research concentrates on defining and measuring energy security, e.g. (Ang et al., 2015) and (Månsson et al., 2014), but no academic consensus has been reached in either composing a clear definition or an indicator that would be useful for political decision-making. The latter is largely due to the lack of a money-metric translation between different dimensions of energy security (Böhringer and Bortolamedi, 2015). Therefore, it is sensible to take into account inter alia the unique geographical, political and economic environment of a nation and analyse energy security of the system per se instead of analysing the complex issue through an indicator.

In November 2016 Finland updated its National Energy and Climate Strategy (the Strategy), which includes targets on e.g. increasing the share of renewable energy sources (RES) by 2030. Concurrently, the issue of generation adequacy[1] during winter demand peaks has been present in the political discourse and in media especially since the record-high demand peak in early 2016 and the cautionary adequacy forecast in 2017 by The European Network of Transmission System Operators for Electricity (ENTSO-E) (ENTSO-E, 2017a). The authors have previously analysed the resilience of the Finnish power system in 2016 (Jääskeläinen et al., 2017; Jääskeläinen and Huhta, 2017) with the conclusion that the system still had enough generation capacity and measures of intervention to cope with severe unexpected faults. However, several simultaneous market trends amplify the stresses regarding security of supply, inter alia the increasing share of weather

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[1] Generation adequacy is defined here as the ability of the totality of generating units to meet demand at all times.

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dependent power production, prolonged low level of electricity market price and decreasing installed capacity of thermal power plants. Moreover, the national strategic objectives of further increasing the share of RES and phasing out coal in energy use both amplify the phenomenon. Thus, the issue of generation adequacy in the Finnish electricity market in the coming decades remains open for debate.

This paper analyses the development of generation adequacy in Finland until 2030 in the energy policy scenarios of the Strategy by modelling the implications of similar conditions as were experienced in early 2016 with the EnergyPLAN simulation tool. In addition to the scenarios in the Strategy, we analyse a third scenario with pessimistic Assumptions regarding investments in power plants and cross-border transmission lines. Moreover, as the Nordic energy system is so heavily dependent on hydropower production, we analyse the interdependence between hydrological situation in the Nordic countries and generation adequacy in Finland by applying the effects of a severe drought in the Nordic energy system in the analysed scenarios. In order to assess the implications of a severe drought on the Finnish energy system, we model the hydrology during the worst drought in the 20th century (1939–1942) with the current hydropower capacity using Finnish Environment Institute's Watershed Simulation and Forecasting System (WSFS). Furthermore, we briefly analyse the environmental impacts of hydropower operations during drought and peak demand in Finland.

Energy-water nexus and the environmental impacts of hydropower utilisation are widely studied research subjects, e.g. (Lam et al., 2016) and (Bakken et al., 2014), respectively. However, there are no extensive analyses on the impacts of a severe drought in the Nordics on generation adequacy in Finland and the environmental impacts of hydropower regulation during a drought. The novelty of this paper is in its interdisciplinary approach that combines hydrological simulations, energy system simulations, environmental assessment and energy policy analysis, and applies these to the official Finnish governmental energy and climate targets. Moreover, the energy-water nexus analysis is particularly interesting in the Nordics, as it is a multinational electricity market with hydropower in an exceptionally significant role.

First, section 2 introduces the current Finnish energy system, including the composition of electricity and heating markets, and the national energy policy targets. Section 3 presents the hydrological analysis and simulations and briefly analyses the impacts of climate change on hydropower availability in Finland. Section 4 introduces the energy system simulations including the input data, tools and results. Finally, section 5 draws conclusions.

2. The Finnish energy system

Due to its geographical location and energy-intensive industry, Finland's consumption per capita is high in both heat and electricity. Industry accounted for 45% of the final energy consumption in 2016 and other significant sectors were space heating (26%) and transport (17%) (Statistics Finland, 2017). Moreover, electricity and heating markets in Finland are linked via combined heat and power (CHP) production, which covers approximately 32% of Finnish electricity production and 67% of district heat production (Finnish Energy, 2017a). The most important primary energy sources in 2016 were biomass (25.9%), oil (23.2%) and uranium (18.2%) (Statistics Finland, 2017). Finland practically imports all of its fossil fuels and uranium, and a majority of the fuels are imported from Russia.

2.1. Electricity and heating markets

The Finnish electricity system is a part of the Nordic wholesale power market, Nord Pool, and hence connected with its neighbouring countries' power markets. Furthermore, Finland is heavily and increasingly dependent on cross-border electricity trade: net electricity imports covered 22.3% of the total electricity consumption in Finland in 2016 (Finnish Energy, 2017b), of which most was imported from Sweden. Therefore, the Finnish power system cannot be analysed in isolation from its neighbouring markets. The main connections are with Sweden, Estonia and Russia, of which the two former are included in the common electricity market. In total, the cross-border transmission capacity allows Finland to import approximately 5100 MW of power from its neighbouring countries, which is more than one third of the record-high hourly demand peak. Moreover, the Strategy includes plans to further increase the transmission capacity between Finland and Sweden in the 2020s, and concrete preparations for a third AC connection started in December 2016.

The Finnish electricity generation mix is highly diversified, comprising high shares of hydro, nuclear and thermal power production and an increasing share of wind power production. Industry and construction covered 47% of the electricity consumption in 2016, residential and agriculture 27%, services and public sector 23% and transmission and distribution losses accounted for 3% (Statistics Finland, 2017). Total installed power capacity in Finland amounted to approximately 16,100 MW in early 2016 (Finnish Energy Authority, 2017). However, as some of the capacity is allocated as system reserves, some is mothballed and the momentary availability of different technologies varies according to many factors, a more relevant figure is the estimated available capacity during the demand peak. Electricity supply by sources, total installed power capacity and the Finnish transmission system operator's (Fingrid) estimation of the available power capacity during the demand peak in 2016 (Statistics Finland, 2017) are presented in Table 1.

Electricity demand in Finland has not increased during the 2010s, but has remained at around 82–85 TWh/a. The low demand has partly been caused by the economic downturn in Finland and partly by the exceptionally warm weather in the past years. The low demand has significantly reduced operating hours of especially condensing power plants, causing the plants to lose their economic competitiveness. Consequently, the commercially active condensing power capacity in Finland has decreased by more than 2000 MW since 2010. The last commercially operative condensing coal plant was partly allocated in the peak load reserves in July 2017 and others have been mothballed or decommissioned earlier. Wind power capacity in Finland and in the Nordics has been growing rapidly – mainly due to national subsidy mechanisms. Wind power capacity in Finland grew from approximately 1000 MW in early 2016 to 2044 MW by the end of 2017 under the current feed-in tariff mechanism. Moreover, wind power capacity in Sweden has experienced similar trends with a greater magnitude, which affects the Finnish power market via availability of electricity imports and their price level.

Due to its geographical location, Finland has a high demand for heat especially during the winter period. A major share of the heating in larger cities is supplied with CHP production whereas a combination of electrical heating, small-scale wood combustion and heat pumps is typically used in remote areas. In comparison with the electricity market, heating market in Finland is much more scattered. Moreover, it is less sensitive with regard to system balance and magnitude of implications of a fault in the system: heat accumulators are widely used to enhance balance in district heating systems and, moreover, an abrupt fault in a district heating network is less tangible to the end-user than one in a power system. Therefore, generation adequacy in heating networks has not been an issue and the focus of the analysis is in the electricity market.

Table 1
Installed power capacity, estimated available power capacity during the winter demand peak and electricity production in Finland in 2016.

Production type	Installed capacity (MW)	Estimated available capacity during demand peak (MW)	Production (TWh/a)
Nuclear power	2780	2780	22.3
Combined heat and power, total	6985	5250	20.8
CHP district heating	*4170*	*3250*	*11.8*
CHP industry	*2815*	*2000*	*9.0*
Hydropower	3180	2550	15.6
Condensing power plants	2160	960	4.4
Wind power	1005	60	3.1
Net Import	–	–	19.0
Total	16,110	11,600	85.1

2.2. National Energy and Climate Strategy

In November 2016, the Finnish Government published a new National Energy and Climate Strategy (Ministry of Economic Affairs and Employment, 2017a), which presents a roadmap to achieve the national energy policy targets. The goal is to systematically set a course for achieving an 80–95% reduction in GHG emissions by 2050. The main targets of the Strategy by 2030 are to increase the share of RES to 50% and the self-sufficiency in energy production to 55%, to halve the use of imported oil for energy comparing to the level of 2005 and to phase out coal in energy production. Moreover, the Strategy aims to increase the share of RES in transport sector to 40% by e.g. increasing the amount of electric vehicles to 250,000 by 2030.

A key tool in the strategy work was calculating possible energy market development via assessing different scenarios. Rather than predictions, the scenarios are built on certain Assumptions projecting different possible future outcomes. The main scenarios are the Basic scenario and the Policy scenario. In addition to the scenarios in the Strategy, we analyse an alternative scenario with a set of more pessimistic assumptions regarding e.g. investments in power plants in Finland and in new cross-border transmission lines. Assumptions in the Alternative scenario are presented in section 4.5.

The Basic scenario assumes that no additional energy policy actions are implemented after the actions taken in spring 2016 or earlier. The scenario sets the baseline with which the required policy actions are compared and the impacts of any new measures on the energy and climate targets can be determined. The share of RES will increase in the Basic scenario, mainly due to an increase in the use of forest chips and waste liquors from forestry. Moreover, the use of heat pumps is estimated to increase with the current trends, while the strong increase in wind power production between 2010 and 2017 will slow down significantly without new policy measures. Final energy consumption is estimated to converge around 315 TWh/a, of which RES should cover approximately 47%. This falls 3 percentage points short from the government's target for 2030. With regard to the targets on energy self-sufficiency and halving the energy use of oil, the Basic scenario falls short 4 percentage points and 12 TWh, respectively (Ministry of Economic Affairs and Employment, 2017b).

The Policy scenario includes policy measures to achieve the national targets set in the Strategy. Some of the measures to reach the targets set in the Strategy are still intangible and mentioned to be specified later on. However, some measures are described briefly in the Strategy, inter alia:

- Technology neutral tendering processes will be organised in 2018–2020 in order to increase RES utilisation in electricity production in the most cost-efficient way
- Increasing the obligation for the share of biofuels in road traffic to 30%
- Coal will be phased out by taxation and subsidies for domestic substitutes in CHP production
- Investment support and tax exemptions for e.g. small-scale distributed energy generation.

3. Hydrological analysis

This section introduces the hydrological simulations in Finland and analyses the indirect impacts of a severe drought based on recent realised dry periods in the Nordics. Moreover, sections 3.4 and 3.5 analyse the environmental impacts of hydropower operations during a severe drought and the impacts of climate change on hydropower production in Finland, respectively.

3.1. Hydrological simulations in Finland

Hydropower production varies depending on the hydrological conditions. In recent years, the annual production of Finnish hydropower has on average been approximately 13 TWh, but varied between 9.3 and 16.6 TWh. Severe droughts are rare in the Nordic countries, but during the past century, droughts have occurred e.g. in 1939–42, 1959–60, 1969, 1980 and 2002–2003 (Bye et al., 2008). During the last 100 years, the driest period in Finland occurred in 1939–1942, during which the precipitation was below average for over three consecutive years. Year 1941 was the driest year in the 20th century with 34–45% lower precipitation than average. This resulted in record low discharges in rivers and water levels in lakes and, consequently, hydropower production in 1941 was only around half of what it was in the late 1930s (Finnish Environment Institute, 2008). However, comparing the hydropower production directly to the present day is not possible, since a large proportion of Finland's hydropower capacity was built only after 1946.

To assess the implications of a drought of similar severity on the energy system today, we model the 1939–1942 hydrological conditions with the current hydropower capacity. Using observations of temperature, precipitation, wind speed and relative humidity of 1938–1942 provided by the Finnish Meteorological Institute, we model the discharge at locations of the current hydropower plants using Finnish Environment Institute's Watershed Simulation and Forecasting System (WSFS) (Vehviläinen and Huttunen, 2005).

The WSFS is a conceptual hydrological model used in Finland for operational flood forecasting and planning of hydropower production as well as research purposes including climate change impact assessment, e.g. (Veijalainen, 2012; Veijalainen et al., 2010). The main part of WSFS is a conceptual rainfall-runoff model based on the Hydrologiska Byråns Vattenbalansavdelning (HBV) model structure developed in Sweden (Bergström, 1976). HBV-type models have been used for both operational forecasting and in research applications especially in the Nordic countries, e.g.

(Arheimer et al., 2011; Steele-Dunne et al., 2008). The WSFS hydrological model consists of over 6000 small lumped sub-catchments in Finland with an average size of 60 km^2 (20–500 km^2) (Vehviläinen and Huttunen, 2005). Water balance simulations are conducted for each sub-catchment, and sub-catchments are connected to produce the water balance and simulate water storage in the river and lake network within the entire catchment. The sub-models in WSFS include a precipitation model calculating areal value and form for precipitation, a snow model based on the temperature-index (degree-day) approach, a rainfall-runoff model with three storages, and models for lake and river routing. WSFS was calibrated against observations of snow water equivalent, extent of snow-covered area, lake water level and discharge of 1981–2015.

WSFS includes all lakes in Finland with an area over one km^2, i.e. approximately 2600 lakes in total. Regulation of lakes in the WSFS is carried out following the current regulation rules and practices. We use model operating rules, where a certain water level for each day corresponds to a certain outflow, and we modified these operation rules to fit the simulated drought situation. We then use WSFS to simulate average daily discharges of the 57 largest hydropower plants in Finland (all plants with a capacity of 10 MW or more) and use the discharges to estimate the weekly average hydropower production with the hydrological conditions of 1939–1942. We convert the discharges to hydropower production using the average ratios of discharge and power production for each hydropower plant.

In addition to the average weekly power production, we also estimate the maximum power production during peak demand. Most of the hydropower plants are located at regulated lakes or downstream of them, allowing short-term increase in power production. We base the maximum simulated hydropower production for the peak demand period in the following energy system simulations on hydrology of January 1942. We estimate it based on the regulation capacity of the power plants situated in lake outlets and in rivers downstream of them taking into account the limits to outflows caused by the regulation permits. Thus, the lake water levels can only be lowered as far as the lower limit of regulation.

3.2. Results of the hydrological simulations

The hydrological simulations of the drought situation result in a significant reduction in annual hydropower production. For example, the annual production with the current hydropower capacity using weather conditions of 1942 is 56% lower than that in 2016 (6.9 TWh/a vs. 15.6 TWh/a). However, the simulations result in a reduction of only approximately 19% in hydropower availability during the peak demand in January comparing to the realised production in 2016 (2235 MW), as dammed storages can be used to increase the discharges during this short period. However, the realised hydropower production during the peak in 2016 fell 315 MW short of the estimated availability. In comparison to the estimated hydropower availability during the peak, the simulated availability during the drought is 29% lower.

Fig. 1 depicts the weekly average hydropower production with weathers of 1941–1942 and 2015–2016. The values from 1940s are based on the hydrological simulations whereas the values from 2010s are based on realised hourly values (Fingrid, 2017). However, it should be noted that hydropower production during 2015–2016 was notably above long-term average.

3.2.1. Adequacy of the hydrological simulations

Simulations carried out with the WSFS model contain several sources of uncertainty affecting the estimate of hydropower production. We carried out the simulations with one calibrated

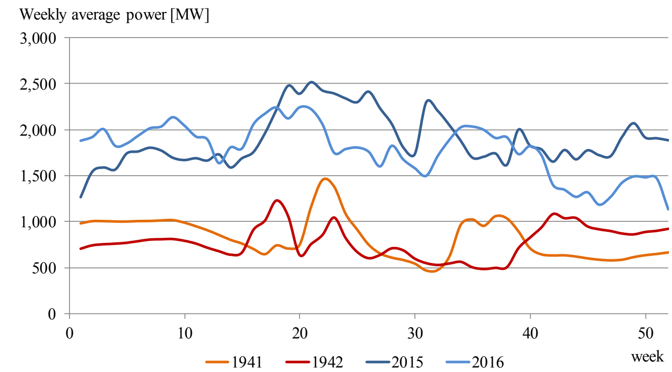

Fig. 1. Weekly average hydropower production in 1941–1942 (simulated, without the peak demand period regulation) and in 2015–2016 (realised).

optimal parameter set for each sub-catchment in the WSFS and modelling uncertainty was not estimated. The severe drought is an extreme event unlike any other in the model calibration period and thus the functioning of the model in these conditions is uncertain. In addition, the meteorological observations of 1939–42 used as input for the WSFS are sparse and contain uncertainties especially in the observed precipitation as snow. However, the discharges simulated with the WSFS model were relatively close to the observed discharges considering these uncertainties and the changes in the watersheds since 1942.

We use a fixed ratio between discharge and power production, which is a simplification and does not take into account the effect of head to the power production. Another source of uncertainty is the estimation on how much the discharge can be increased during the peak demand period. The estimation is based on the regulation rules and limits and maximum capacities of hydropower plants. Environmental considerations (see section 3.4) and possible frazil ice formations could limit the discharges from what has been modelled here. For these reasons, the uncertainties in the modelled discharges can be notable.

While the decrease in annual production was large, the modelled decrease in production during peak demand was more modest (19% smaller than realised in 2016). Considering this and the uncertainties discussed, the modelled hydropower production during peak demand is more likely to be an overestimate than an underestimate of the power production during a severe drought.

3.3. Impacts of a drought in the neighbouring countries on the Finnish energy system

As described in section 2, Finland has cross-border transmission lines to Sweden, Russia and Estonia. Moreover, there is a transmission line between Northern Finland and Norway, but it is not in commercial use. Interconnection capacities between bidding areas and countries in the Nordics are presented in Fig. 2.

Finland's net electricity imports from Sweden (and indirectly from Norway) were over 15 TWh in 2016. The Swedish and Norwegian power markets are both larger than the Finnish market and they are both much more reliant on hydropower than Finland. Production and consumption figures in the Swedish and Norwegian power markets in 2016 are depicted in Table 2. Average annual hydropower production in the 2000s has been approximately 68 TWh in Sweden and 127 TWh in Norway, although hydropower capacity in Norway has been growing gradually. However, variation in the inflow to the Norwegian hydropower system has been around 60 TWh in the last few decades (Norwegian Ministry of Petroleum and Energy, 2015). Consequently, annual fluctuations

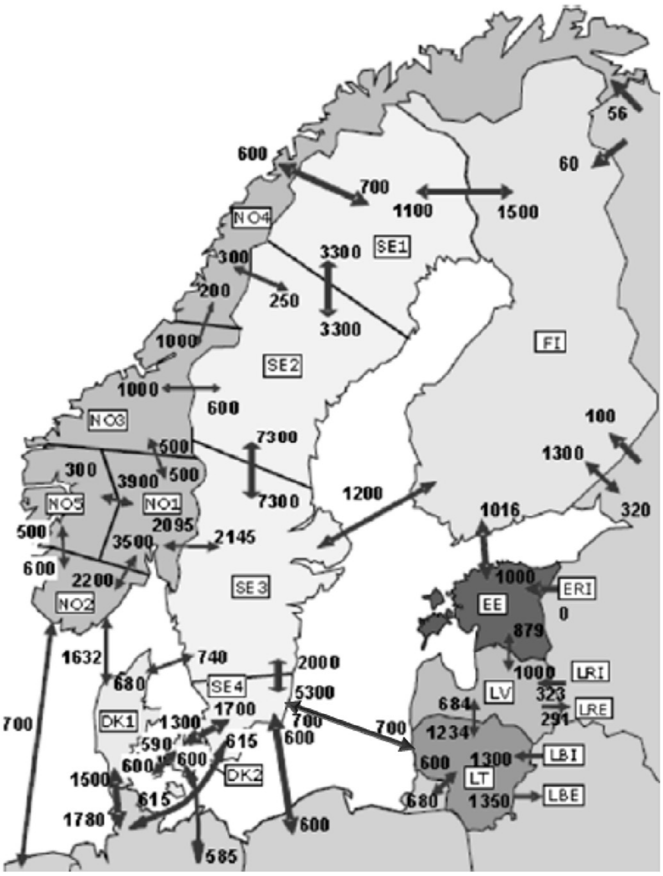

Fig. 2. Interconnection capacities between bidding areas in Nord Pool area. Figure altered from (ENTSO-E, 2014).

Table 2
Electricity production and demand in 2016 in Finland, Sweden and Norway (ENTSO-E, 2017b).

	Finland	Sweden	Norway
Total installed power capacity[a] (GW)	17.0	39.4	32.0
Installed hydropower capacity[a] (GW)	3.2	16.2	30.8
Annual consumption (TWh)	85.1	139.8	133.2
Annual demand peak (GWh/h)	15.1	26.6	24.5
Annual production (TWh)	66.0	151.5	148.8
Annual hydropower production (TWh)	15.6	61.2	143.4
Share of total production	23.6%	40.4%	96.4%

[a] In the end of 2016.

in hydropower production affect generation adequacy much more in Sweden and Norway than in Finland.

During dry years, both Norway and Sweden become net importers of electricity, whereas e.g. in 2016, both countries' net electricity exports were more than 10 TWh. Most recently, this occurred for both countries in 2006 and 2010. In 2006, the summer was extremely dry in Finland and in the Nordics. Consequently, the monthly electricity spot price was lower in Finland than in Sweden between March and December (Nord Pool, 2017). Stresses regarding generation adequacy in the Nordics typically take place in the winter, but in addition to the drought in 2006, there were outages in Swedish nuclear reactors due to technical reasons (NordREG, 2007). The lack of hydropower availability was largely compensated by increases in Finnish and Danish thermal power generation, which both have decreased notably since. Year 2010 was dry in general, resulting in deficits of around 30 TWh in the Nordic reservoirs by the winter 2010/2011 (NordREG, 2011). Moreover, Swedish nuclear power generation was again low in 2010. Thus, day-ahead price in the Finnish bidding area was again lower than that of Sweden throughout most of the winter and, hence, Sweden was a net importer of electricity from Finland due to the drought.

The modelled drought of 1939–1942 is significantly more severe and lengthier than the dry periods in recent years. It has been estimated that the inflows to Norway's reservoirs (2005 system) were approximately 25% below average during 1941 and 12–16% below average in 1939 and 1940 (Bye et al., 2006). Similar reduction in inflow can also be assumed for Sweden. While the significant reservoirs in Nordics (around 85 TWh in Norway and 34 TWh in Sweden (NordREG, 2011)) can be used to buffer the effect of decrease in inflow, the storage capacity is not enough for a three-year long drought. Therefore, when electricity imports from Sweden to Finland stop during relatively modest dry periods such as in 2006 and 2010, it is safe to assume that during an extreme drought like in 1939–42, no electricity imports from Sweden to Finland would be available during the demand peak.

The Russian government implemented a mechanism called capacity delivery agreement (CDA) in order to incentivise investment in electricity generation capacity starting from 2010. Approximately 40 GW of generation capacity has been launched by CDAs in 2010–2015, namely nuclear, hydro and thermal generation (Gore et al., 2016). However, demand for electricity has not grown as much as was forecasted prior to the financial crisis and hence the mechanism has resulted in a surplus of power capacity in Russia. Production capacity in Western Russia, where the Finnish and Russian power systems are connected, surpasses the annual demand peak by almost 70% (12.6 GW vs. 7.5 GW) (ÅF-Consult Ltd, 2016). Moreover, Russia is less dependent on hydropower production than the Nordic countries and approximately two thirds of electricity in Russia is produced with natural gas (Gore et al., 2016). Therefore, it is reasonable to assume that electricity trade between Finland and Russia would not be restricted in case the severe drought affected also Western Russia, especially when assuming an electricity price level reflecting an imminent generation inadequacy in Finland.

Estonia has a very modest hydropower capacity and is currently self-sufficient regarding generation capacity during winter peaks. Estonia is also a transit country of electricity: in 2015, Estonia's net imports from Finland were 5.0 TWh and net exports to Latvia were 5.9 TWh, which is a significant flow of electricity comparing to Estonia's own annual consumption of 7.4 TWh (Competition Authority of Estonia, 2016). However, Latvia and Lithuania have notable hydropower capacities, and a transmission line between Lithuania and Sweden, NordBalt, was commissioned in late 2015. Hence, a severe drought in Sweden would also affect Finland indirectly via the availability of electricity imports from the Baltic countries. Furthermore, more than 80% of electricity in Estonia is produced with oil shale and majority of it in Narva Power Plants. Most of these plants are constructed between 1959 and 1973 and some of them will most probably be decommissioned by 2024 (Competition Authority of Estonia, 2016). Therefore, the availability of thermal capacity and hence the self-sufficiency of electricity supply in Estonia in 2030 remains uncertain. This paper assumes that no restrictions in electricity imports from Estonia occur in the stress test in 2020, but that the decommissioning of thermal capacity in the 2020s reduces the available electricity imports by 200 MW in 2030.

In addition to the planned new transmission lines between Finland and Sweden, there are numerous plans to increase transmission capacity inside the Nord Pool region and between Nord Pool and Central Europe (ENTSO-E, 2017c). We assume, however, that alleviating congestion inside Sweden and Norway or between the countries does not solve the lack of hydropower availability during a severe drought. Moreover, we assume in this study that the planned new transmission lines between Nord Pool region and Central Europe (and UK) will not notably ease the stresses related to generation adequacy during the peak demand in Finland by 2030. However, this is a complex issue with conflicting views among industry experts. On the one hand, the increasing interconnection capacity will increase the demand for the cheap and flexible Nordic hydropower and hence decrease its availability in Finland. On the other hand, the new transmission lines will make the Central European thermal power more available to the Nordic countries during peak demand.

3.4. Environmental impacts of hydropower operations during drought and peak demand in Finland

Under the modelled circumstances, a hydrological drought causes river discharges to decrease considerably from their normal values. However, during a peak demand period we assume that hydropower plants situated in locations with available storage reservoirs, mostly at outlets of natural but regulated lakes, will use their storage during the peak demand as much as possible to increase the production. This means that during January, the discharges will be high for two to three weeks and water levels in regulated lakes will fall much more rapidly than normally during this period. During normal hydrological years, water levels of the major regulated lakes tend to fall approximately from January until April.

The impact this unusual hydrological situation will have on the environment will depend strongly on the watercourse in question. Some rivers with hydropower plants are heavily dammed, i.e. there are several dams with a long dammed reservoir making the river a string of pools. Therefore, changes in discharges have little effect on the water levels. In other rivers, there are no possibilities to increase the discharges at all due to the regulation permits, which for example stipulate that during low water levels the outflow from the regulated lake must follow the natural rating curve. In some rivers, however, the environment may suffer from the rapid changes in discharge during a peak demand period due to increased erosion and changes in habitats, for instance. In other cases, the lake biota will suffer because of the earlier-than-normal drawdown of water levels in January.

Other possible impacts of the large discharge include formation of frazil ice. Weather during the modelled situation before the peak demand period in 1942 was cold enough for icecaps to form, which usually protects from frazil ice formation. However, the large increase in discharge could break the ice cover in some locations whereas other locations remain ice-free all winter due to high flow speeds. In these locations, the combination of low temperatures and high discharges during the peak demand period could cause formation of frazil ice, causing the need to decrease discharges and hence the hydropower production.

The modelled changes in discharges would cause damage to river and lake biota and habitats on a local scale. To decrease the negative impacts, the increase in discharge during the peak demand period would need to be smaller than the modelled discharge. However, since the modelled changes in discharge remain within the regulation permits, the demand for energy can be seen as a higher priority than the local environmental impacts during the peak demand period. Thus, the increase in discharge could take place despite the environmental impacts. Severity of the energy security threats would hence be the determining factor for the priorities. The formation of frazil ice might force some decreases in discharge, but it should not affect the overall hydropower production greatly.

Case example of Lake Kemijärvi, one of the most important regulated lakes in terms of hydropower production in Finland, is presented in the following section. Lake Kemijärvi is regulated with Seitakorva dam, the 6th largest hydropower plant in Finland (with 34 MW of capacity and 511 GWh/a average production (Kemijoki Oy, 2017)). The regulation affects all the dams downstream in Kemijoki (7 dams), which together with Seitakorva constitute approximately 31% of the average hydropower production in Finland.

3.4.1. Lake Kemijärvi

Water level regulation is the major pressure for littoral biota in Lake Kemijärvi (Sutela et al., 2013). The ecological status of littoral zone biota, macrophytes and macroinvertebrates, as well as fish has remarkably deteriorated (Sutela et al., 2013). The negative impacts on biota are mainly due to the large percentage of productive zone, which is disturbed during the winter. The average winter drawdown is the largest in Finnish natural lakes, 6.75 m, which is 12-fold compared to the natural state (0.55 m (Marttunen and Hellsten, 2003)). The ice layer extends down to the bottom, causing sediment to freeze and to be partly eroded by scouring (Marttunen et al., 2006). The depth of the frozen zone depends on the water level in the mid-winter (early February (Marttunen and Hellsten, 2003)). In addition to the aquatic ecosystem, decreasing winter water levels have negative impacts on recreational use and fishing on the lake.

In the modelled situation, the drought itself has little effect on Lake Kemijärvi water level, since the drought was substantially milder in Northern Lapland than in other parts of the country and because the regulation can adapt to changes in discharge effectively. However, during the peak demand period in January, the increase in discharge and hydropower production would cause the water level to fall earlier than normal (Fig. 3). This earlier drawdown of water level would cause the water level in early February to be approximately 1.8 m lower than average observed water level at that time in 1981–2010. This would have negative impacts on water quality in closed bays, macrozoobenthos and freeze-sensitive macrophytes.

3.5. Impacts of climate change on the hydropower production in Finland

Climate scenarios project a 1–3 °C increase in temperature by 2030 and modest increases (2–11%) in precipitation in Finland (Finnish Meteorological Institute, 2009). Runoff is estimated to increase less than precipitation due to increase in evapotranspiration and runoff may even decrease in some scenarios (Veijalainen, 2012). The seasonal variation of runoff will change with larger runoff in winter and less runoff during spring floods. For hydropower production, this means in most cases a more even distribution of discharges and less spill off, although in some cases changes in current regulations are needed in order to achieve the full benefits of this change. These changes in seasonal variation will on average mean increase in discharge during winter, when the peak demand occurs. Summer discharges will on average decrease. Moreover, extreme low temperatures causing the peak demand are expected to become less common with climate change (Finnish Meteorological Institute, 2009).

These are, however, the changes in averages. Changes in extremes conditions, such as in extreme droughts, may be different. Some extreme weather events, such as heavy precipitation, are projected to become more common in the future, but there is no clear evidence of changes in the probability of extreme drought in Finland (IPCC, 2012).

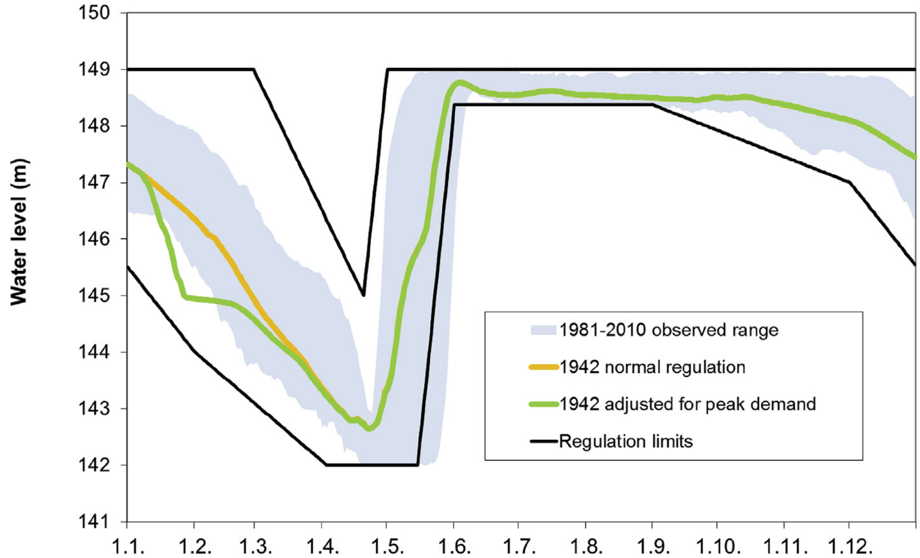

Fig. 3. Drawdown of water level during peak demand period in early January in Lake Kemijärvi.

4. Energy system simulations

This section introduces the used simulation tool, EnergyPLAN, the applied stress test in the simulated energy systems and Assumptions regarding inter alia power capacities and demands in the analysed scenarios. The simulated scenarios in different years are constructed so that they correspond with the assumptions and estimations in the scenarios of the Strategy.

4.1. The EnergyPLAN model

The energy system simulations in this paper are executed using a publicly available simulation tool, EnergyPLAN (version 12.5), which is developed and maintained by the Sustainable Energy Planning Research Group at Aalborg University. The tool simulates national energy systems on an hourly basis, including electricity, heating, cooling, transport and industry sectors. The algorithms of the model are not presented in this paper, but are thoroughly documented in (Lund, 2015). EnergyPLAN has been widely used for modelling systems with a high share of CHP production, e.g. (Lund and Mathiesen, 2015) and (Zakeri et al., 2015).

EnergyPLAN is a deterministic input-output simulation tool with an hourly time resolution of a full year (8784 h). The model inputs are inter alia annual energy demands, technology specifications of production facilities and annual profiles of inflexible production methods. All annual profiles are input as deterministic hourly distribution patterns. Output of the simulation consists of hourly system operation, fuel consumption and system costs. Fig. 4 depicts the flow diagram of the major components in the EnergyPLAN model. Energy sources are depicted with white background, conversion technologies with yellow, storage and exchange with blue and demands with orange.

EnergyPLAN has two different strategies for simulation: technical and market economic. The technical simulation strategy prioritises all available domestic production before importing any electricity, whereas the market economic strategy prioritises imported electricity in case its price is lower than the short-run marginal costs of domestic production. Moreover, the market economic scheme reflects the nature of dammed hydropower as a market-balancing instrument more accurately, whereas the technical strategy distributes flexible hydropower production evenly throughout the year. The market economic strategy hence reflects the dynamics of the Nord Pool market more accurately and, therefore, we apply it in this study.

4.2. The stress test

We put generation adequacy in the simulated scenarios under a stress test in years 2020 and 2030 by applying the implications of a severe drought in Finland and in the Nordics during otherwise similar conditions as were witnessed during the demand peak in early 2016. The simulated scenarios assume hydrology of 1942, preceding the severe droughts in 1939–1941. We base the impacts of the drought on the Finnish energy system on the conducted hydrological simulations, which provide the input data for hydropower availability in the energy system simulations. The indirect impacts via reduced availability of cross-border transmission capacity we base on analysis of realised, less severe droughts in the 2000s.

The stress test applies similar demand profiles of electricity and heat as were realised in 2016, although we scale the level of demand to match the estimations for different years in the Strategy. Electricity demand profile and the production profiles of inflexible production methods, such as wind, run-of-river hydro and nuclear power, are from Fingrid's open data service (Fingrid, 2017). We estimate the annual profile of heating demand based on the running 5-h average of district heating CHP production. We assume power plant cost data and technical specifications according to Energienet.dk's report Technology Data for Energy Plants (Danish Energy Agency, 2016) in the simulations. We derive the power capacity in Finland based on Finnish Energy Authority's power plant register (Finnish Energy Authority, 2017) and on the described development in the background report of the Strategy (Ministry of Economic Affairs and Employment, 2017b).

4.3. The Basic scenario

Assumptions regarding power capacity development in the scenarios are not described in detail in the Strategy, but the background report of the Strategy (Ministry of Economic Affairs and

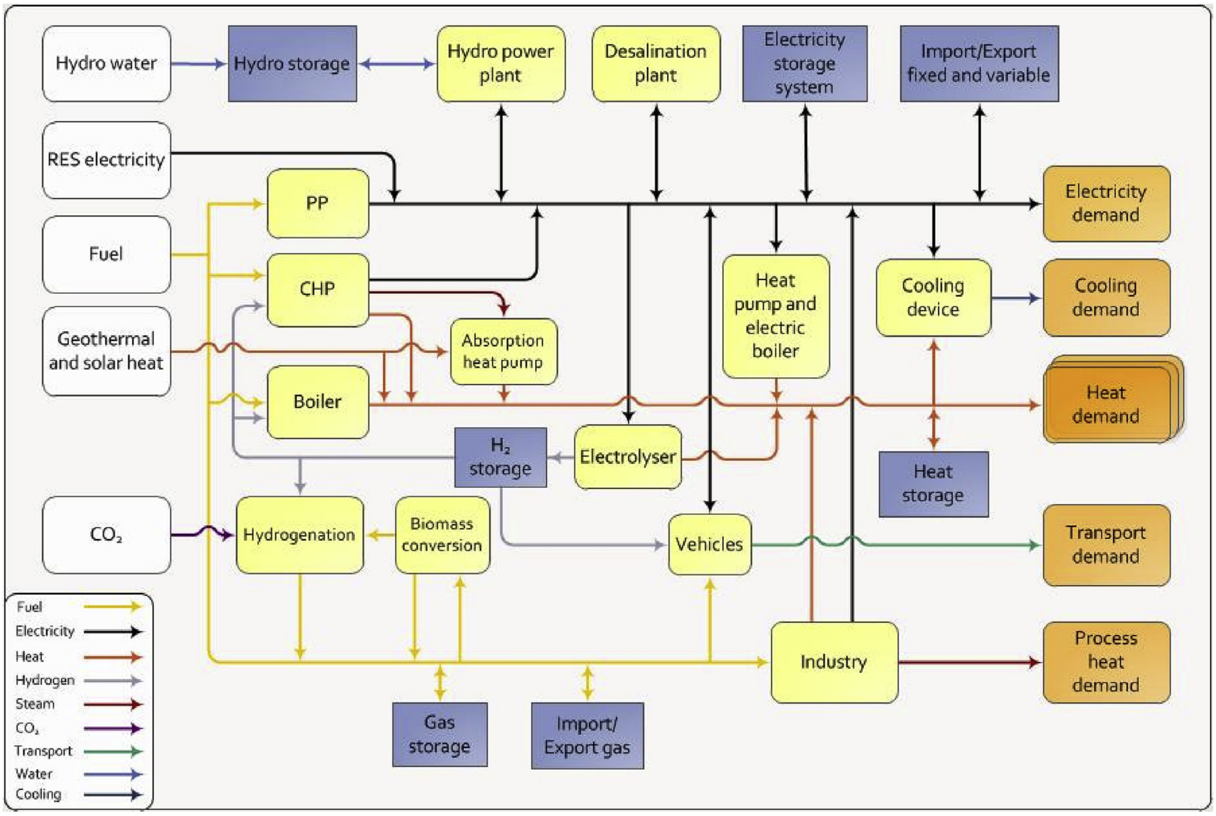

Fig. 4. Flow diagram of EnergyPLAN model's major components (Lund, 2015).

Employment, 2017b) presents estimations of available power capacities in the Basic scenario during winter peaks in 2020 and 2030, which are depicted in Table 3. The estimations assume an availability of 6% for wind power, but as the applied stress test assumes equivalent conditions as were experienced during the record-high demand peak in 2016, we assume an availability of 16% of the installed capacity for wind power. As can be seen from the table, district heating CHP capacity will decrease notably by 2030. However, we assume that this does not affect the available heating capacity, as retiring CHP plants are replaced with heat only boilers. The background report of the Strategy provides estimations on the magnitudes of the demand peaks in 2020 and 2030, which are approximately 15,440 MWh/h and 16,120 MWh/h, respectively.

4.4. The Policy scenario

Neither the Strategy nor its background report describe the detailed development of power capacity in the Policy scenario and, hence, the capacity is derived using the estimations of the Basic scenario, annual energies in the Policy scenario and other contents of the Strategy and its background report. As regards generation adequacy, no differences in the Basic and Policy scenarios have yet emerged by 2020. However, the Policy scenario assumes that the currently last commercially operative condensing coal plant, Meri-Pori, is allocated in the strategic reserves by 2030. Moreover, the Policy scenario assumes that another 400 MW of district heating CHP capacity has been mothballed or allocated in the strategic reserves due to the phase-out of coal in energy production by 2030. Estimated available power capacities during winter peaks in 2020 and 2030 in the Policy scenario are presented in Table 4. Electricity consumption in the Policy scenario is one TWh higher in 2030 than that in the Basic scenario and the difference comes from industry, construction and transport sector. Assuming that the additional energy demand is divided evenly throughout the year, the demand peaks in 2020 and 2030 are 15,440 MWh/h and 16,235 MWh/h, respectively.

Table 3
Estimated available capacity during the winter peaks in 2020 and 2030 in the Basic scenario.

Production type	Available capacity during winter peak in 2020 (MW)	Available capacity during winter peak in 2030 (MW)
Hydro power	2610	2610
Nuclear power	4380	5130
Condensing power plants	725	725
Combined heat and power, total	5395	5000
CHP district heating	*3115*	*2545*
CHP industry	*2280*	*2455*
Wind power	320	385
Transmission capacity	4800	6000
Total	18,230	19,850

Table 4
Estimated available capacity during the winter peaks in 2020 and 2030 in the Policy scenario.

Production type	Available capacity during winter peak in 2020 (MW)	Available capacity during winter peak in 2030 (MW)
Hydro power	2610	2610
Nuclear power	4380	5130
Condensing power plants	725	160
Combined heat and power, total	5395	4645
CHP district heating	*3115*	*2145*
CHP industry	*2280*	*2500*
Wind power	320	510
Transmission capacity	4800	6000
Total	18,230	19,055

4.5. The Alternative scenario

As the Policy scenario is just one plausible projected energy market pathway, we wanted to analyse the aims of the Strategy with an alternative set of Assumptions regarding especially the supply side, i.e. the Alternative scenario. The Alternative scenario assumes prolonged low level of electricity prices throughout the 2020s and hence a lack of willingness to invest in new power capacity. Most of the retiring CHP plants are replaced with heat only boilers due to the lack of economic feasibility of CHP electricity production and, moreover, Hanhikivi 1 nuclear power plant investment does not materialise. Neither Balticconnector nor growing liquefied natural gas (LNG) markets manage to restore the economic feasibility of natural gas in Finland. Therefore, its utilisation keeps its declining trend, resulting in an additional reduction of 485 MW in available CHP capacity during winter peak by 2030. Moreover, investment in the third transmission line between northern Finland and Sweden does not realise. Meri-Pori condensing coal power plant was allocated in peak load reserves in July 2017 and it is assumed to stay in the reserves for the remainder of its technical lifetime. As regards electricity demand, electric vehicles have developed faster than predicted in the Strategy, increasing the annual electricity demand by one TWh. The demand peaks in 2020 and 2030 are hence 15,440 MWh/h and 16,350 MWh/h, respectively. Estimated available power capacities during winter peaks in 2020 and 2030 in the Alternative scenario are presented in Table 5.

4.6. Results of the energy system simulations

As the Strategy was published in late 2016, no notable differences in the Basic and Policy scenarios have yet occurred by 2020. The Alternative scenario has 565 MW less capacity available during the winter peak due to Meri-Pori condensing coal plant being allocated in peak load reserves. However, the commercially available power capacity and transmission capacity after supplying the demand during the peak still amount to more than 2200 MW. Sums of the available commercial power capacities and available transmission capacities in different scenarios in 2020 and 2030 are presented in Table 6. All in all, generation adequacy is much better in each of the simulated scenarios comparing to that in 2016 (Jääskeläinen et al., 2017) due to the expected deployment of Olkiluoto 3 nuclear power plant.

Regarding a severe drought affecting only Finland in 2020, the system could withstand its impacts without noteworthy energy security threats in each scenario. The simulated decrease in hydropower availability during the peak would only be approximately 19% compared to the realised production in January 2016 due to the ability to use storage reserves during a short peak demand period. However, a drought affecting also Sweden and Norway would already cause a deficit of 360 MW in the Basic and Policy scenarios and 925 MW in the Alternative scenario due to the reduced availability of electricity imports.

The simulations result in a notable improvement in generation adequacy by 2030 in the Basic scenario, slight improvement in the Policy scenario and an alarming drop in the Alternative scenario, from 2225 MW–160 MW. The difference between the scenarios Basic and Policy is caused by the phase out of coal in energy use and the assumption that most coal-fired district heating CHP plants are replaced with heat only boilers in the Policy scenario. Main reasons for the improved availability of capacity are explained via the deployment of Hanhikivi 1 nuclear power plant (1200 MW) and the two new transmission lines between Finland and Sweden (800 MW + 400 MW). The difference between the scenarios Policy and Alternative comes from the absence of Hanhikivi 1 and the 800 MW transmission line between Finland and Sweden. Moreover, the Alternative scenario assumes a stronger trend in decreasing CHP capacity due the lack of competitiveness of natural gas in power production.

The scenarios Basic and Policy could withstand the Finnish drought also in 2030 without any measures of intervention. However, the Alternative scenario has a deficit of 590 MW already during a drought affecting only Finland. As regards a drought affecting also Sweden and Norway, the impacts are much more

Table 5
Estimated available capacity during the winter peaks in 2020 and 2030 in the Alternative scenario.

Production type	Available capacity during winter peak in 2020 (MW)	Available capacity during winter peak in 2030 (MW)
Hydro power	2610	2610
Nuclear power	4380	3870
Condensing power plants	160	160
Combined heat and power, total	5395	4160
CHP district heating	*3115*	*1660*
CHP industry	*2280*	*2500*
Wind power	320	510
Transmission capacity	4800	5200
Total	17,665	16,510

Table 6
Available production and transmission capacity after supplying the demand during demand peaks in 2020 and 2030 in different scenarios.

Scenario	Available capacity during the winter peak in 2020 (MW)	Available capacity during the winter peak in 2030 (MW)
Basic	2790	3730
Basic, Finnish drought	2040	2980
Basic, Nordic drought	−360	−820
Policy	2790	2820
Policy, Finnish drought	2040	2070
Policy, Nordic drought	−360	−1730
Alternative	2225	160
Alternative, Finnish drought	1475	−590
Alternative, Nordic drought	−925	−3590

alarming than in 2020. This is mainly due to the increasing dependency on cross-border transmission capacity between Finland and Sweden to cover the demand peak. The deficit in the scenarios Basic and Policy could technically be supplied with the available measures and strategic reserves, but the deficit of 3590 MW in the Alternative scenario is alarming. Figs. 5 and 6 depict the electricity demand and supply during the peak demand day in the Policy scenario in 2030 during a normal hydrological situation and a Nordic drought, respectively.

4.6.1. Adequacy of the energy system simulations

The occurrence of extreme weather events such as cold periods or droughts are difficult to predict. The conducted simulations are deterministic and we do not take a stance on the probability of the combination of an extreme long-lasting drought and a record-high demand peak. However, both the extreme drought in the 1940s and the record-high demand peak in 2016 are events that have materialised, and we wanted to analyse their combination as a black swan event, i.e. an event that is extreme in its nature and difficult to predict.

We chose the EnergyPLAN tool for the energy system simulations as it suits for the comprehensive analysis of an energy system including both heating and electricity sectors. However, EnergyPLAN is not an optimal tool for the analysis of a set of national energy systems with a complex web of interconnections and hence we based the indirect impacts via reduced import availability on a more qualitative analysis. Moreover, EnergyPLAN's timespan for simulations is one year whereas the analysed drought lasted for over three years, the tool lacks an option for temporal restrictions in import capacity of electricity and the tool does not consider ramp-up rates of power plants. Nevertheless, the simulations provided us with the desired insight on both the impact of a severe drought on generation adequacy in Finland and the development of generation adequacy in the scenarios presented in the Strategy.

As for the sensitivity regarding downside risks in the simulations, there is no significant difference between the scenarios. Olkiluoto 3 nuclear power plant will be deployed in each analysed scenario and will hence be the most critical component in the system with a capacity of 1600 MW, and wind power availability in the stress test is already low enough to include mainly upside risk. The inclusion of the Alternative scenario in the analysis hence depicts the plausible worst-case scenario regarding the development of generation adequacy in the Finnish power market.

5. Discussion and conclusions

We have analysed the Finnish energy system and its development in different energy policy scenarios, simulated hydropower availability during a period of severe drought in Finland and estimated the indirect impacts of a drought in Finland's neighbouring countries. Moreover, we have simulated generation adequacy in the analysed scenarios in 2020 and 2030 with the EnergyPLAN

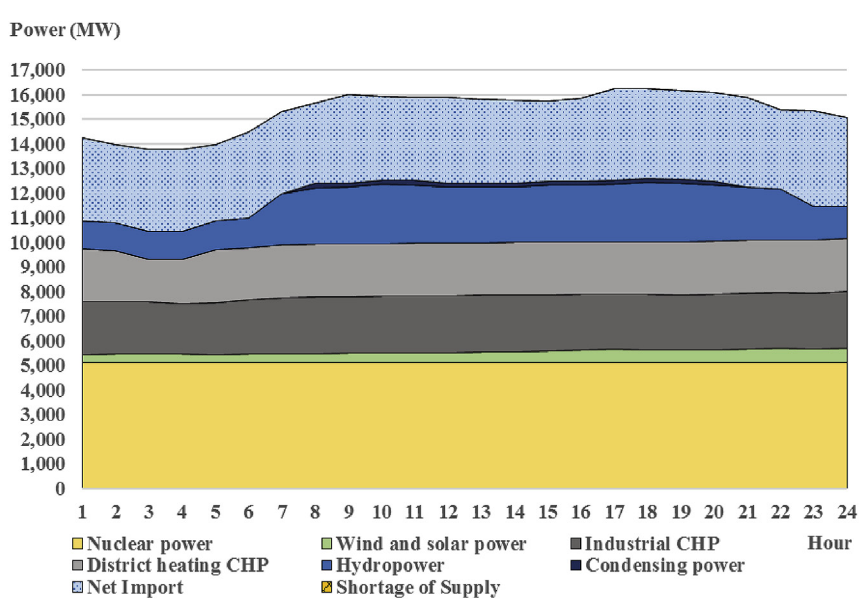

Fig. 5. Electricity demand and supply during the peak demand day in the Policy scenario in 2030 during a normal hydrological situation.

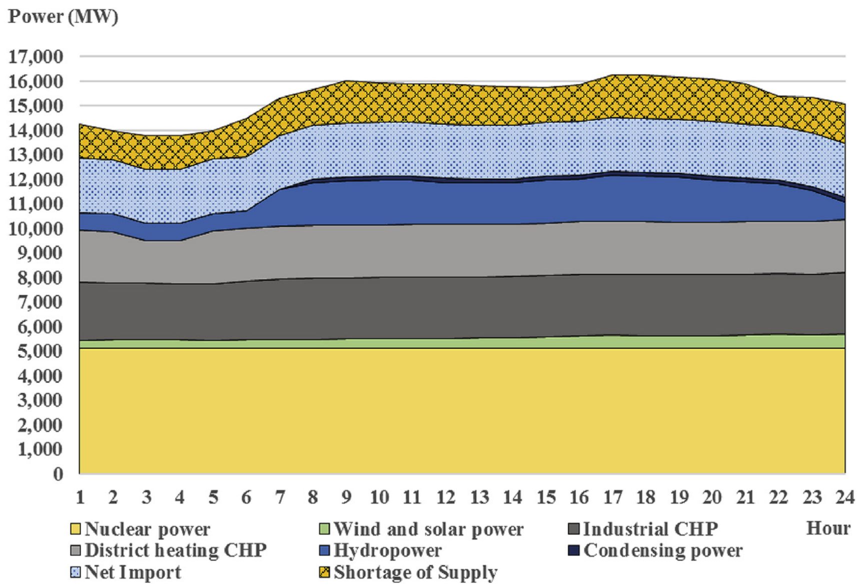

Fig. 6. Electricity demand and supply during the peak demand day in the Policy scenario in 2030 during a severe drought affecting the Nordic region.

simulation tool by applying the implications of a severe drought during otherwise similar conditions as were witnessed during the record-high demand peak in Finland in early 2016. Furthermore, we have briefly analysed the environmental impacts of hydropower regulation during drought and peak demand and the impacts of climate change on the Finnish energy system.

Excluding the impacts of a drought, our results show that in both of the scenarios presented in the new Energy and Climate Strategy of Finland, Basic and Policy, the stresses related to generation adequacy will ease by 2030 comparing to those in 2016. This is mainly due to the deployment of two new nuclear power plants, Olkiluoto 3 and Hanhikivi 1, and the planned new transmission lines between Finland and Sweden. These new power plants and cross-border transmission lines improve generation adequacy more than what the forecasted growth in the annual demand peak and the reduction in thermal power capacity in Finland affect in total. As regards the Alternative scenario with inter alia no investment in Hanhikivi 1 or in the third transmission line between Northern Finland and Sweden, the stresses related to generation adequacy will grow significantly by 2030.

In spite of hydropower accounting for a notable share of power capacity and electricity production in Finland, an extreme drought occurring merely in Finland has a relatively low impact on generation adequacy during winter peaks due to storage of dammed hydropower. The demand peak occurring in January ensures that, despite a severe drought, dammed hydropower storages are available during a relatively short-term demand peak. However, Finland's electricity market is strongly affected by those of Sweden and Norway, which both have significantly higher shares of hydropower than Finland. Hence, as an extreme drought would likely occur in the Nordic countries simultaneously, the drought would affect the Finnish energy system more strongly via cross-border electricity trade.

To understand the indirect implications of a simultaneous drought in the Nordic countries, we analysed the Nordic power system and occurred dry periods in the 2000s with notably lower severities than that experienced in the 1940s. According to the analysis, it is reasonable to assume that no cross-border electricity trade between Finland and Sweden would occur during the winter demand peak and a drought with the same severity as the one in 1940s. Consequently, the simulations resulted in deficits of 820 MW, 1730 MW and 3590 MW in 2030 in the Finnish power capacity during the peak demand in the Basic, Policy and Alternative scenarios during a severe drought in the Nordics, respectively. The deficits in the Basic and Policy scenarios could still be handled with the current estimated demand-side flexibility and different strategic reserves, but the deficit in the Alternative scenario would require more drastic measures, such as Fingrid applying rolling blackouts in the power system.

The estimated demand-side flexibility in the electricity spot market is currently approximately 400 MW and it is more likely to increase than decrease by 2030. Moreover, peak load reserves were increased from 300 MW in 2016 to 729 MW in July 2017 and it remains to be seen, how much of the retiring thermal capacity is allocated to some form of capacity reserves. Furthermore, development of the power markets in Finland's neighbouring countries includes a lot of uncertainties, such as the future of Swedish nuclear power units, the economic competitiveness of thermal power in the Baltic countries and the availability of Norwegian hydropower in case Norway increases its transmission capacity outside Scandinavia.

The current electricity price level in Finland does not encourage investment in new power capacity and, as electricity market price is practically determined by the short-term marginal costs of the last realised supply bid in the energy-only model, investment in wind or nuclear power is not about to increase the average price. Concurrently, there is a consensus among industry experts about two issues: first, CHP capacity in Finland will decrease with the current trends and, secondly, this is not a favourable trend regarding energy security. CHP production has been a backbone of the Finnish energy system due to its high thermal efficiency and flexibility, and hence it would not be surprising, if the government applied some new incentives to keep it as a part of the system. Therefore, the magnitude of the consequences of Finnish utilities replacing retiring CHP plants with heat only boilers is yet to be seen.

The debate regarding generation adequacy often concentrates on the supply-side. However, there is vast potential in demand-side measures both in industry and in households, of which the latter accounted for more than two thirds of the electricity consumption during the demand peak in 2016. Demand-side flexibility in the Finnish industry and in households has been studied recently by e.g. (Helin et al., 2017) and (Olkkonen et al., 2017), respectively. Households suit well for short-term flexibility, but demand-side measures in households are currently hindered by the lack of economic incentives and aggregators. However, there is a growing interest and pilot projects in aggregation of for example electric water heaters into virtual power plants. The potential of flexibility in industry, on the other hand, is always case specific, and the high ramp-up costs in especially process industry can make short-term flexibility infeasible.

As for energy security impacts of climate change on the Finnish energy system, the simulated scenarios indicate that climate change could actually work in favour of generation adequacy by increasing the precipitation and discharges during the winter season and decreasing the occurrence of extremely low temperatures. However, climate change can increase the intensity of the extremes in inter alia precipitation and temperatures.

There are several issues increasing the uncertainty regarding the future of the Nordic energy system, inter alia the fate of Swedish nuclear power units and what replaces the Narva power plants in Estonia in the 2020s. Another issue worth a more thorough scrutiny is the impacts of increasing transmission capacity between Nord Pool area and Central Europe (and UK) on storage reservoirs and hydropower availability in the Nordics. These require a modelling tool more suitable for multi-regional analysis and are subjects of future research.

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