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RESEARCH ARTICLE

Contributing factors for electricity storage in a carbon-free power system

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Summary
The Government of Finland is targeting carbon neutrality by 2035. Increasing electrification emphasizes the need for significant emission reductions in power generation. As reduction in power generation emissions is partly realized by increase in intermittent energy sources, electricity storage may become an important part of a carbon neutral power system. This study investigates the behavior of electrical storages as a part of a large-scale national carbon-free power system model. As a case study, a three-year model of a carbon-free Finnish power system set in 2050 with the aim to identify various factors affecting electricity storage, and the results are compared with literature. The proposed case study features various scenarios with a national power system with very high amounts of renewables and a significant hydro capacity, while amount of combustion-based energy production is minimal. In addition, hydrological stress scenarios representing historically severe drought years were introduced. The amount of electricity storage needed was found to be most affected by nuclear and electricity trading capacities, which is consistent with literature findings. The data period used as basis for modeling also affected the need for electricity storage, as interannual variations in renewable production were found to have a large effect on modeled results. The needed electricity storage capacities increased significantly in the stress scenarios. The electricity storage need was found to be seasonal in nature, but this may be partly due to missing demand flexibility within the modeled power system, which caused very large individual storage discharge peaks. The results emphasize the need to take several years of historical data into account to ensure system availability in different conditions.

Highlights
• Nuclear energy was found to decrease system costs in a 100% carbon-free power system.
Multi-year modeling is essential to secure system availability due to the important role of hydropower and seasonal wind variability.

Electricity storages were found to be seasonal in nature. The main reason was exceptionally low windiness during individual periods, which resulted in large but temporarily short power deficits due to insufficient flexibility obtained from hydropower and power imports. This was especially evident in stress scenarios and mainly contributed to the higher costs in low-nuclear scenarios.

Detailed hydropower modelling of historically exceptional dry seasons in Finland was utilized as one stress scenario. Exceptionally, dry long-term period increased the need for electricity storages significantly due to the lost flexibility offered by hydro and reduced electricity import capacities.

**KEYWORDS**
carbon-free power system, electricity storage, Finland, hydropower, nuclear power, wind power

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1 | INTRODUCTION

The Government of Finland has announced an ambitious climate policy of achieving carbon neutrality by 2035. Carbon neutrality not only requires cutting down on fossil fuel emissions, but also the preservation of carbon sinks. As electrification is predicted to advance, the role of power generation will take an ever-increasing role in the formation of greenhouse gas (GHG) emissions. Therefore, the transition to a power generation model supporting the goals of carbon neutrality will be important. For example, the Intergovernmental Panel on Climate Change (IPCC) defines carbon neutrality as net zero emissions, which “are achieved when anthropogenic emissions of greenhouse gases to the atmosphere are balanced by anthropogenic removals over a specified period.” The anthropogenic removals include, among other things, the means for “enhancing biological sinks of CO₂.” In this study, the enhancement of biological sinks is achieved through minimizing the usage of biomass in power generation. Limiting biomass in a system with large shares of renewable power generation mandates the usage of storages, to balance out the variability of renewables. It is important to study how the storages are used, so that proper storage technologies can be investigated in the future.

1.1 | Current Finnish power system

Finnish electricity production was 65-77 TWh/a, and consumption 79-90 TWh/a between 2000 and 2019, with net electricity imports covering the production deficits. The share of net import of the electricity demand has varied between 5.5% and 23.4%. Currently, wind power covers 7% of yearly electricity demand, and this has increased rapidly. The share of photovoltaic (PV) has also increased but remains marginal at 0.2% of yearly power production. Nuclear power provides around a quarter of the electricity demand, and this share has remained quite constant over recent decades. The production share of condensing power has decreased quickly. Hydro power has large yearly variations, as it has produced between 10.8% and 19.1% of annual electricity demand in recent decades. Due to cold climate and energy-intensive industry, electricity demand per capita in Finland is very high. According to the World Bank, per capita electricity consumption in 2014 was 15 250 kWh/year, which is roughly double compared with average Organisation for Economic Co-operation and Development values.

Finland is part of the Nordic electricity market, known as an early example of successful international liberalized market, and has also been able to cope with supply shocks, such as the drought in 2002-2003. The Nordic electricity market is especially reliant on hydropower, as it produces around 50% of total power generation in the Nordics. However, due to the recent increase of intermittent electricity generation, electricity storage solutions have attracted research interest. Currently, electricity storage solutions in the Nordic countries, with the exception of pumped hydro storage (PHS), are not yet widely used. On the other hand, hydropower includes significant storages in reservoirs and lakes, which offer flexibility. Of the Nordic countries, Norway has 1.44 GW and
Sweden 0.1 GW of PHS installed as of 2019. Current commercial utility-scale battery projects in Nordic countries are either used for frequency control or have received subsidies. In addition, battery-scale projects are still quite small in scale. The largest battery project currently under construction is in Ylikkälä, Finland, where a 30 MW/30 MWh battery is currently under construction to be used in battery-based grid services.

1.2 Problem of diminishing carbon sinks in Finland

Biomass has several advantages in electricity production. For instance, it can be used in CHP plants, which attain efficiencies of 90% in Finland, and accounts for a large share of Finnish energy production. However, there are problems related to the wood biomass usage, especially due to diminishing carbon sinks.

The amount of carbon sinks has been decreasing in Finland. During the 2010s, the land use, land-use change and forestry (LULUCF) carbon sinks in Finland decreased from 20.8 Mt CO\(_2\) eq. in 2010 to 14.7 Mt CO\(_2\) eq. in 2019. This decrease in carbon sinks equates to around half of all emissions in the transport sector in 2019. Therefore, there is a great concern related to the total carbon sink amount in Finland. The vast majority of the carbon sinks in Finland are forest biomass. Biomass usage directly affects the depletion of carbon sinks. In addition, there are several new forestry industrial plants, which will significantly increase the usage of biomass in the future. In February 2021, an investment decision was made by Metsä Group to construct a new bioproduct mill in Kemi, with the intention of sourcing pulpwood from Finland. This was the biggest forestry industry investment in Finnish history.

Because of the probable increase in the use of biomass in the forestry industry, in this study, it was investigated whether it is possible to avoid the use of biomass in electricity production, thus allowing it to be allocated exclusively for industrial use. The only biomass used in this work is black liquor, which is a direct by-product of the forestry industry and is used to cover the electricity usage of the forestry industry itself. It is also kept as a constant.

1.3 Literature review

Several studies have proposed the large-scale integration of renewable energy systems for Finland and in a broader context also for the whole of Europe. In these studies, electricity storage has been included as part of the solution at least in some of the presented scenarios. These and additional similar papers were selected for literature review. The selected studies mostly feature an hourly resolution and a single operation year. Table 1 summarizes the properties of these studies. The investigated studies all present increased variable renewable energy (VRE) of varying degrees. In References 13 and 18, only wind and PV are allowed as generating technologies, while Reference 23 also allows concentrated solar power. Reference 14 features a wide variety of renewable technologies and includes a no-biomass scenario. In Reference 12, nuclear power and biomass are also deployed. In Reference 16, gas turbines are also included in addition to renewable sources. References 17 and 19-22 are capacity expansion studies, where some fossil technologies are also allowed. Reference 24 features a low-carbon power system, and it includes some gas, biomass, and nuclear capacities. The electricity trading was featured and mentioned in all studies, except in References 12 and 22. Reference 20 additionally features multiple different base years for modeling. Multiple different weather-years as well as single years are investigated in Reference 24. Reference 25 features a literature review of electricity storage amounts based on other studies.

The selected studies feature different electricity storage technologies. While nearly all the selected studies feature batteries, hydrogen or power-to-gas options were additionally considered in several studies as were compressed air storages. Some studies only considered short-term storages. The roles of electricity storage in the papers varied from not essential to predominantly featured. Storages play different roles and are of differing importance if they are long-, medium-, or short-term storages. Storages were found to offer diminishing marginal returns and to be susceptible to variations in renewable energy generation. Various generation technologies were reported to work well with different storage technologies. For instance, PV generation was found to correlate with increased Li-ion battery charging, while onshore and offshore wind correlated with hydrogen storages. However, some studies found storages themselves to add negligible benefits if the system contains well-interconnected electricity transmission regions. The absence of seasonal storage may make some technology configurations infeasible. However, battery resources were also deemed to be insufficient when intermittent resources were at seasonal lows, and dispatchable technologies were found to be needed in the absence of technological breakthroughs. The results vary depending on how the studies were modeled. Studies of multiple interconnected regions were less susceptible to renewable variations and, therefore, required less storage. Storage capacities were also found to be sensitive to selected weather scenarios. The storage requirement
| Model                                      | Scope                                       | Role of storage                                                                 | Notes                                                        | Reference |
|--------------------------------------------|---------------------------------------------|---------------------------------------------------------------------------------|--------------------------------------------------------------|-----------|
| EnergyPlan, HR, OYm                        | Finland                                     | Features a power-to-gas storages, which are featured predominantly.              | Features a “100% recarbonized” assumption. Includes heat modeling. | 12        |
| GENSYS, HR. Contains evolutionary strategy in solving. | Interconnected regions in Europe, Middle East, and North Africa | SMT storage technologies mutually exchangeable.                                 | LT storage impacts the LCOE the most.                        | 13        |
| PLEXOS modeling package used. CDS, HR.     | Europe                                      | Storage not found to be essential                                                | Assumes fully flexible biogas                                | 14        |
| GenX, HR, OYm, CDS                         | “Northern” and “Southern” climate regions from United States. | Energy storages act as fast-burning balancing resources.                        | Firm low-carbon resources are needed to optimize the system. Storages treated as li-ion batteries. | 15        |
| Linear optimization problem, HR, OYm      | Europe with 30 regions.                     | Hydrogen storages utilize wind while batteries PV.                              | 95% decrease in carbon emissions                             | 16        |
| Eleplan-m, CDS, HR, OYm                    | South-Eastern Europe                        | Energy storages found to be essential in achieving decarbonization.             | GHG emissions could be reduced by 97.4% compared to 2016 levels. | 17        |
| Extended time frames, HR or 15 minutes resolution. | California                              | Seasonal storage, usually charging during spring, discharged during winter.                      | 100% renewable power system assumed with wind and solar energy production. Similar wind capacities required larger storages than corresponding solar ones. | 18        |
| Enelytix security-constrained unit commitment model, HR | Regional, New England, USA                  | Daily balancing of intermittent generation                                       | Seasonal intermittent generation lows cause storage problems | 19        |
| Gen X generation expansion planning model. HR, OYm. | Italy                                      | Lowers system costs, marginal benefits decreasing.                               | Multiple years of VRE and load data usage recommended.      | 20        |
| REMix-CDS Uses perfect foresight, partial greenfield.HR, OYm | Europe, multiple countries                | Varies depending on storage technology.                                         | SMT storage particularly important for periods of low renewable generation. | 21        |
| AMPL, solved using CPLEX LP solver. HR, OYm | Regional, Texas, California, USA            | Optimizes deployment of renewables by reducing costs and curtailment.           | Uses 2010-2012 as base years. Storage deployment also cost effective in Texas without introducing renewables. | 22        |
| Multi-Region Energy System Optimization Model HR, OYm | Global                                     | Balancing the variable generation. Power generated only from wind and solar.    | Thermal energy storage seen as the best storage technology. Hydropower neglected. | 23        |
| High RES model, HR, CDS                    | UK                                          | Electricity storage amounts are sensitive to weather-years The spatial deployment patterns remain same. | Includes scenarios up to 80% VRE. Electricity storage modeled as NaS battery. Interannual weather patterns found critical. | 24        |
| A polynomial regression model in MATLAB based on multiple other studies, | Europe                                      | Electricity storage becomes vital when VRE share increase above 40–50%.          | Electricity storage capacities where only analyzed up to 95% VRE due to large divergence. | 25        |

Abbreviations: CDS, capacity installation and dispatch separated; HR, hourly resolution; LT, long term; OYm, one-year modeling; SMT, short and medium term.
also found to increase linearly as share of VRE increases, but when 40%-50% share of VRE is exceeded, the storage needed increases dramatically. Storage capacities were also found to vary depending on the installed storage technologies. In Reference 18, a smaller amount of battery capacity was required when compared with hydrogen storage.

1.4  |  Research goals

This article presents a case study of a carbon-free power system for Finland set in 2050, which contains power generation technologies, which produce neither fossil nor biogenic carbon emissions, except for forest industry by-products. The modeling approach of the case study presented here is based on methods described in References 26 and 27. For this case study, hydropower modeling was done with in-depth models by the Finnish Environment Institute, and realistic inflow values were used in the hydro stress scenarios. In the Finnish electricity market, hydropower is a very important component, and thus, detailed hydrological inflow scenarios are essential. Thus, the scenarios presented in this paper should not be viewed as already presented in References 26 and 27. This case study contains technological restrictions leading to inflexible base energy production but includes dispatchable hydropower. This differs from most of the studies looked at in the literature review, as they mostly either included fossil technologies or only allowed wind- and solar-based technologies. None of the selected studies had as significant hydro component as our proposed case study. The stress scenario for hydro power is also a novel component that is not found in the literature study.

This article has three main objectives to better understand the properties of a carbon-neutral power system in Finland: first, to identify a relationship between the nuclear capacity and various key metrics in this work; second, to identify the importance of a period of several years on the modeling results by varying the amount of historical data available for the model, and third, to identify the role of electricity storage and how it would be used. To get a more realistic look at the power system, the only balancing component of the system, hydropower, is placed under a stress test. It is expected that nuclear power decreases the costs, as was seen already in Reference 27; however, an optimal amount of nuclear capacity is also expected to be found. In addition, as the low-wind periods were already seen to be significant in earlier works, it is expected that the selection of the modeling years should also have an impact on the results, especially on the dimensioning of electricity storages. This article does not make any definite pre-considerations on the electricity storage technologies, and all calculations are made with battery-related parameters. The results are then discussed with the previous results found in the literature.

2  |  MATERIALS AND METHODS

2.1  |  General model description

The model used in this work operates under greenfield planning and overnight investment assumptions and uses historical hourly data spanning a three-year period. The model includes an electricity storage and allows for the import and export of power. Five different power generation technologies are included in the model. The included generation technologies are wind, PV, nuclear, and hydropower as well as black liquor, which was included as a constant source of power to cover the needs of the Finnish forestry industry. The historical hourly data for PV and wind production as well as electricity demand are from Fingrid’s open data service. In addition, data from the Finnish Environment Institute were also utilized in the construction of hydro inflow scenarios. This paper also utilizes hydrological data to evaluate the effects of an extended drought in Finland. These inflow scenarios have been used in Reference 30 for example. The main methods of the model are described in the following subsections. For details, as to how both wind and PV as well as electricity demand, including electric vehicle demand has been normalized and curated, please refer to Reference 26. The technologies assigned by the model depend on the specific scenarios, but in all scenarios, the optimal PV, wind power, and storage capacities are assigned by the model.

2.2  |  Hourly power balance

An hourly power balance is enforced in the model. For each modeled hour \( t = [1,2,26280] \), the production of power is always set equal to the power demand. The power balance equation is given in Equation (1):

\[
P_{D,t} + P_{S,t} + P_{CL,t} + P_{CL,t} = P_{GI,t} + P_{GH,t} + P_{I,t} \quad \text{for} \ t,
\]

where \( P_{D,t} \) is the power demand [MWh/h], \( P_{S,t} \) is the power consumed by the electricity storage (negative values for when the storage is supplying power) [MWh/h], \( P_{CL,t} \) are the storage losses, \( P_{GI,t} \) is the fixed power generation [MWh/h], \( P_{GH,t} \) is the flexible hydro generation [MWh/h], \( P_{CL,t} \) is the curtailed power [MWh/h], and \( P_{I,t} \) is the imported power (negative for power export) during hour \( t \) [MWh/h].
The priority order of power production is presented in Figure 1.

As can be seen from Figure 1, the model compares the fixed power generation of each hour to the hourly power demand. If fixed power generation exceeds power demand, the electricity storage is first charged up to capacity, and then, power is exported up to export capacity, and finally, power is curtailed. Conversely, if fixed power generation is not enough, first hydro is dispatched up to capacity, and then, electricity is imported up to capacity, and finally, electricity storage is discharged.

The power balance is upheld in the model by one of the following ways if no other methods are available:

- In case of power excess, power is curtailed until balance is reached.
- In case of power deficit, power is supplied from the storage until balance is reached.

There is no set limit to either of these values on an hourly level.

What should be noted, however, is that both hydro dispatch and electricity storage dispatch affect the feasibility constraints.

In addition, the power balance is defined to be used later in the calculations in Equation (2):

\[ P_{B,t} = P_{I,t} + P_{Gf,t} + P_{Gh,t} - P_{D,t}, \]  

where \( P_{B,t} \) is the power balance [MWh/h]. The power balance shows the situation before the electricity storage is used. This is the case even when there is excess power, as the hourly power export is calculated by considering the possibility of charging electricity storage.

## 2.3 Power generation

Power generation is split into two different parts, the fixed power generation and flexible hydro power generation. Fixed power generation comprises of wind, PV, black liquor, and nuclear generation, as well as run-of-river hydro. The fixed power generation depends on the installed capacities as well as hydro inflow scenarios. Wind and PV productions are acquired by multiplying the installed capacities with the hourly capacity factors, which are derived from the hourly data from Fingrid. The black liquor power production is assumed to be a constant for each modeled hour. Nuclear power capacity is divided into two parts, the traditional part being the existing and forthcoming large nuclear power plants, including the Olkiluoto 3 and Pyhäjoki plants. They are assumed to operate at capacity, except during their maintenance periods, when they are not operating. Olkiluoto 3 is assumed to operate at 1600 MWh/h, except between 1.8 and 20.8 when undergoing maintenance. Respectively, Pyhäjoki is assumed to operate at 1200 MWh/h, except 11.6-30.6, when it has been set to undergo maintenance. The maintenance periods do not change and are the same for each year in the modeling. In addition, it is possible to include small modular reactor (SMR) nuclear power plants in the model. They are assumed to be running at a constant 0.95 capacity factor, as small individual plants are assumed to have evenly spread maintenance.

![Figure 1](image)

**Figure 1** Order of calculation used in the model
times. The components of fixed power generation are presented in Equation (3):

$$P_{\text{Gf},t} = P_{\text{Gwind},t} + P_{\text{GPV},t} + P_{\text{Gnucl},t} + P_{\text{Gbl},t} + P_{\text{GhydroROR},t},$$

(3)

where $P_{\text{Gwind},t}$ is the hourly wind power production [MWh/h], $P_{\text{GPV},t}$ is the hourly PV production [MWh/h], $P_{\text{Gnucl},t}$ is the hourly nuclear power production [MWh/h], which is comprised of the earlier mentioned two plants and SMR, $P_{\text{Gbl},t}$ is the constant hourly black liquor production [MWh/h], and $P_{\text{GhydroROR},t}$ is the hourly run-of-river hydro generation [MWh/h], the calculation of which is presented in Equation (4).

Run-of-river hydro is determined from the hourly hydro inflows, by multiplying these values with the run-of-river factor, assumed in this work to be 45%. The same methodology for calculating this was applied in References 26 and 27. In addition, flexible hydro generation $P_{\text{Gflex}}$ is deployed if the fixed power generation does not exceed the demand, according to the constraints defined in Section 2.7.

### 2.4 Electricity storage calculations

The electricity storage is charged or discharged under the principles shown in Equation (4):

$$P_{\text{s},t} = \min \left( P_{B,t} \ast \eta_{\text{s,charging}}, P_{\text{charge cap}} \right), \text{if } P_{B} \geq 0$$

$$P_{\text{s},t} = \max \left( \frac{P_{B,t}}{\eta_{\text{s,discharging}}}, P_{\text{discharge cap}} \right), \text{if } P_{B} < 0,$$

(4)

where $P_{s,t}$ is the hourly charge or in negative cases discharge of the electricity storage [MWh/h], $\eta_{\text{s,charging}}$ is the charging efficiency $[-]$, $\eta_{\text{s,discharging}}$ is the discharging efficiency $[-]$, $P_{\text{charge cap}}$ is the maximum charging power [MW], and $P_{\text{discharge cap}}$ is the maximum discharging power [MW] of the electricity storage. In this model, the maximum charging capacity was set at 2500 MW, while due to the nature of the electricity storage as the final supplying power, a discharging cap was not set, so in this sense, it can be considered infinite in this modeling. The charging and discharging efficiencies were 0.85 and 0.95, respectively. No self-discharging losses were considered. Later, in the economic calculations, the larger discharging powers are taken into consideration in the grid costs, where these are dependent on the maximum measured charging or discharging powers. The electricity storage level is calculated using Equation (5):

$$E_{s,t} = \left\{ \begin{array}{ll}
\min(E_{s,max}, E_{s,initial} + P_{s,t} \ast 1h) & \text{if } t = 1 \\
\min(E_{s,max}, E_{s,t-1} + P_{s,t} \ast 1h) & \text{otherwise}
\end{array} \right.,$$

(5)

where $E_{s,t}$ is the electricity storage level at hour $t$ [MWh], $E_{s,max}$ is the maximum capacity of the electricity storage [MWh], and $E_{s,initial}$ is the initial electricity storage level [MWh], assumed to be 50% of the maximum capacity.

### 2.5 Hydro inflow scenarios

Two different sets of hydro scenarios were used in this model. The normal scenarios were implemented with the data retrieved from Reference 29. The reference data, which contained daily inflows between 1978 and 2014, were used as a basis, and from these inflows, different percentiles were taken. In the normal inflow scenarios, inflow scenarios 75th, average, and 25th percentile scenarios were generated. Leap days were not considered, so all scenarios contain 365 daily values. This process is given in greater detail in Reference 26. Stress scenarios were named scenarios “1941” and “1942,” because they are based on the record droughts which occurred in Finland during those years. For each of the 3 years in the model, it is possible to select one inflow scenario. The possible hydro scenarios are presented in Figure 2.

As can be seen from Figure 2, the hydro scenarios used in the normal flow scenarios have a similar hourly distribution, whereas the stress scenarios do not have the usual seasonal spring inflow peak caused by melting snow and are much flatter. Average hourly inflows and total inflow energies are shown in Table 2.

The difference between the scenarios is also very significant in the inflow energies and average hourly inflows. In the normal scenarios, the hydro scenarios are 75th, average and 25th for first, second, and third years, while in the stress scenarios, scenario 1941 is chosen for the first and third years, while scenario 1942 is chosen for the second year.

#### 2.5.1 Construction of hydro stress scenarios

The hydrological stress scenarios were estimated based on hydrological modeling of the historical drought event in 1939-1942. This drought event was the worst drought in the period with discharge observations for most of Finland, and it lasted over 3 years. The estimated return period of the drought ranges from 1 in 250 years in Southern and Central Finland to considerably more common, but still drier than average in Northern Finland.
Many hydropower plants in Finland have been built after this drought, and there are not enough discharge or hydropower production observations to estimate the hydropower production with current production capacity in such a drought event. Therefore, a hydrological model was used to estimate the discharges during the drought event at present-day major hydropowerplants in Finland, and hydropower production was estimated based on these discharges.

The hydrological model used was Finnish Environment Institutes Watershed Simulation and Forecasting System (WSFS), which covers the entire country and transboundary watersheds. It is the hydrological model used for operational flood forecasting in Finland (www.vesi.fi) and by the major hydropower producers for planning purposes. The conceptual rainfall-runoff model forming the main part of WSFS is based on the Hydrologiska Byråns Vattenbalansavdelning (HBV) model structure developed in Sweden. HBV-type models have been used for both operational forecasting and in research applications especially in the Nordic countries.

Observed temperature, precipitation, wind speed, and relative humidity from the Finnish Meteorological Institute from 1938 to 1942 were used as input of the hydrological model to simulate the discharges. Present-day configurations and regulation rules and practices were used for lakes and reservoir. The results are simulated daily discharges at 57 largest hydropower plants in Finland (all plants with a capacity of 10 MW or more). These discharges are then used to estimate the weekly average hydropower production with the hydrological conditions of 1941-1942. The simulated discharges are converted to hydropower production using the average ratios of discharge and power production for each hydropower plant. The regulation of lakes and reservoirs is not optimized, but they represent an average weekly value. More details about the modeling of the severe drought of 1939-1942 can be found in Reference 31.

2.6 | Hydropower calculations

From the daily inflows shown in Figure 2, the hourly inflows are calculated using Equation (6):

$$E_{\text{inflow},t} = \frac{125}{21} * E_{\text{inflow},d} \text{ when } t \in d,$$

where $E_{\text{inflow},t}$ is the hourly hydro inflow at hour $t$ [MWh/h], $\frac{125}{21}$ a constant to convert from unit GWh/week to MWh/h, and $E_{\text{inflow},d}$ the daily inflow given to the model. This means that the daily inflow is evenly distributed to all hours within that day. For example, for hours $h = [124]$, the inflow is given by the inflows of the first day and so on. From the hourly inflows, the hourly fixed hydropower generation is calculated using Equation (7):

$$P_{\text{HydroROR},t} = \alpha * E_{\text{inflow},t},$$

where $P_{\text{HydroROR},t}$ is the fixed hydropower generation at hour $t$, and $\alpha$ is the run-of-river factor, which has been set at 0.45. Dispatchment of variable hydropower is given in Equation (8):

![Figure 2](image-url) | Hydro inflow scenarios used in this model

| Inflow scenario | Average | 75th | 25th | 1941 | 1942 |
|-----------------|---------|------|------|------|------|
| Sum of inflow energies (TWh/a) | 12.12 | 14.87 | 8.28 | 7.47 | 7.14 |
| Average hourly hydro inflow (MWh/h) | 1501 | 1841 | 1024 | 925 | 884 |
where $P_{\text{hydrop},\text{normal}}$ is the hydrop capacity in normal use. For normal non-stress scenarios, this equals $P_{\text{hydrop},\text{normal}}$, which is the maximum hydrop capacity set at 3150 MW, whereas for stress scenarios, it is set individually, to prevent over dispatchment of hydropower. $E_{\text{reservmax}}$ is a maximum limit for the reservoir content, which is set at 99% of the reservoir capacity, if, during the previous hour, the reservoir exceeds 99% of its capacity, then hydropower is dispatched at full capacity, regardless of whether it results in increased power export or curtailment. Conversely, $E_{\text{reservmin}}$ is the minimum limit for the reservoir content, set at 1% of the reservoir capacity, and if the reservoir is at lower capacity, no extra hydropower is dispatched, even if there is a power balance deficit.

Hydro reservoir is calculated as described in Equation (9):

$$
P_{\text{Gh},t} = \begin{cases} 
\text{MIN}(\text{MAX}(P_{D,t} - P_{\text{Gh},t}, 0), P_{\text{hydrop},\text{normal}} - P_{\text{GlydroROR},t}) & \text{if } E_{\text{reserv},t-1} \geq E_{\text{reservmax}}, \\
0, & \text{if } E_{\text{reserv},t-1} < E_{\text{reservmin}}
\end{cases}
$$

(8)

where $P_{\text{hydrop},\text{normal}}$ is the maximum hydrop capacity set at 3150 MW, whereas for stress scenarios, it is set individually, to prevent over dispatchment of hydropower. $E_{\text{reservmax}}$ is a maximum limit for the reservoir content, which is set at 99% of the reservoir capacity, if, during the previous hour, the reservoir exceeds 99% of its capacity, then hydropower is dispatched at full capacity, regardless of whether it results in increased power export or curtailment. Conversely, $E_{\text{reservmin}}$ is the minimum limit for the reservoir content, set at 1% of the reservoir capacity, and if the reservoir is at lower capacity, no extra hydropower is dispatched, even if there is a power balance deficit.

Hydro reservoir is calculated as described in Equation (9):

$$
E_{\text{reserv},t} = \begin{cases} 
\text{MIN}(E_{\text{reserv},max}, E_{\text{reserv},initial} + E_{\text{inflow},t} - P_{\text{hydrop}}) & \text{if } t = 1, \\
\text{MIN}(E_{\text{reserv},max}, E_{\text{reserv},t-1} + E_{\text{inflow},t} - P_{\text{hydrop}}) & \text{otherwise}
\end{cases}
$$

(9)

where $E_{\text{reserv},t}$ is the reservoir content at hour $t$ [GWh], $E_{\text{reserv},max}$ is the capacity of the reservoir, set at 5530 GWh, and $P_{\text{hydrop}}$ is the total hourly hydro usage [MWh/h], which is the sum of the run-of-river hydro and flexible hydro.

### 2.7 Objective function

The objective function of this modeling was to minimize the resulting levelized cost of electricity (LCOE), shown in Equation (10):

$$
\text{LCOE} = \sum_{\text{technology}} \left( \frac{C_{\text{technology}} * c_{\text{technology}}}{d * 10^6 * \frac{1}{1-\left(\frac{r}{1-r}\right)^{n}}} \right) + \frac{c_{\text{o\&m}}}{d * 10^6} \text{technology} \in \{\text{wind, solar, hydro, nuclear, storage, transmission}\},
$$

(10)

where $C_{\text{technology}}$ is the capacity of the technology [MW or MWh], $c_{\text{technology}}$ is the cost of the power or energy capacity of a specific technology [$\text{€/MW or €/MWh}$], $r$ is the discount rate, $d$ is the electricity demand in the total scenario [TWh], $n$ is the lifetime of the technology [−], and $c_{\text{o\&m}}$ is the operation and maintenance costs that are either fixed or flexible costs [$\text{€/MW or €/MWh}$]. The capacities of the technologies are either set as parameters, or they are decided by the model. The grid capacities are calculated in another way, however. Grid capacities are comprised of two different parts. The first part is a flat cost depending on the import capacity used in the scenario. The second part depends on the maximum discharge power of the storage. However, this value is set at a minimum of 2500 MW if storage exists. These values are then summed up, and this represents the installed grid capacity in the model.

The optimization formula is as follows. The modeling results are subjected to constraints, both in the hydro dispatchment as well as the electricity storage usage. Specifically, hydropower cannot be used more than the total inflow. In addition, the hydro storage must be non-negative during all hours. This is checked by comparing the hydro reservoir at the last modeled hour to the initial hydro storage. The electricity storage constraint is ensured by setting the electricity storage at positive values during all hours. This is shown in Equation (11):

$$
\begin{align*}
\min & \quad \text{LCOE} \\
\text{s.t.} & \quad E_{s,t} \geq 0 \forall t \\
& \quad E_{\text{reserv},26280} \geq E_{\text{reserv},\text{initial}} \\
& \quad E_{\text{reserv},t} \geq 0 \forall t.
\end{align*}
$$

(11)

### 2.8 Formulation of stress scenarios

In stress scenarios, the inflow scenarios are changed, and electricity import and export are restricted to 50% of that of the normal scenarios. In addition, hydro dispatchment is limited by adjusting the maximum available capacity $P_{\text{hydrop},\text{normal}}$. However, these scenarios operate on the same generation capacities as the normal scenarios. In the scenarios, after the inflow scenarios have been changed, hydro dispatch is limited by limiting $P_{\text{hydrop},\text{normal}}$, except for the 200 hours, where the power balance would be the most negative with these new values. For these values, the hydro dispatch is only limited by the total hydro capacity. This balancing is done with Excel Solver, and after this has been completed, the new electricity storage capacity is set, so that the electricity storage...
values are not negative. This process is presented in the scheme in Figure 3.

Methodologically, the formulation of stress scenarios is the same as in References 26 and 27, with the exception of the consideration of the 200 worst power balance hours. This method was introduced to cut down the resulting storage capacities in stress scenarios, as power balance deficits were very heavily temporarily concentrated. The used methodology is still a simplified behavior, as full capacity would not be reached in a drought, and changes would be introduced more gradually.

2.9 | Formulation of scenarios

In this case study, nine different scenarios related to nuclear power as well as three different scenarios related to the modeling data and four different trading scenarios were considered. Common economic parameters used in all scenarios are shown in Table 3.

In all scenarios, the wind, PV, and storage capacities were decided by the model. However, in addition, in some scenarios, SMR nuclear capacity was also assigned by the model. Initial parameters for different scenarios are shown in Table 4. In addition, the charging efficiency of the storage was set at 85%, and discharging efficiency set at 95%. Here, self-discharge was not assumed. The electricity demand was set at an average of 105 TWh/a; thus, for the three-year scenarios, total electricity demand was set at 315 TWh. This is based on the high electrification scenario presented in a long-range emission development study of Finland. The LCOE was also calculated for the nuclear scenarios using an economic lifetime of 40 years, to see how this affects the total costs of the scenarios.

The scenarios utilizing only 2017, 2018, or 2019 data are using the same assumptions as basic scenarios. However, these scenarios utilize only wind and solar data from the respective years. The demand data are also only used from the same years, and it has been re-scaled to match the same 105 TWh/a annual power consumption.

Electricity import and export capacities are based on electricity import and export data from Fingrid, which indicates current import and export capacity of 5260 and 3780 MW and planned capacity planning upgrades until 2030. For the basic 2050 scenario, total import and export capacities of 7460 and 6480 MW were assumed. Additional variants were used as presented in Table 5. In stress situations, the import and export capacities are assumed to be half of the capacities stated in Table 5. High trading scenario is applied to the previously mentioned “No SMR” scenario, as this scenario in particular benefits from additional trading capacity. The trading restrictions in Medium and Autarky trade scenarios were applied to the basic scenario.

2.10 | General model solving

The model was solved with Excel Solver. However, due to the non-linear behavior of the used hydro in the hydro dispatch, the “generalized reduced gradient (GRG) nonlinear” method was used. It was found that finding
optimization results depended on the starting point of the solution. The impact of this was minimized using the same “basic scenario” as a starting point for other scenarios. The research problem formulation was clearly on the limits of the tool used, with each scenario workbook being 100 MB in size and very slow to solve.

3 | RESULTS

All basic scenarios had a hydro power production of 11.76 TWh/a, and stress scenarios had a hydro production of 7.08 TWh/a, except for the Max nuclear and Autarky scenarios, which had hydro productions of 11.10 and 6.43 TWh/a, respectively. All scenarios also had a black liquor power production of 5.34 TWh/a.

3.1 | Different nuclear capacity scenarios

The results for the basic scenarios with differing amounts of nuclear capacity can be seen in Table A1. The LCOE tends to decrease the more nuclear capacity is installed, up to a point. In addition, increasing nuclear capacity decreases the installed wind capacity dramatically. The solar capacity behaves in a more interesting way, as it tends to have similar capacities of around 1200 MW in
several different scenarios. In addition, the required storage decreases the more nuclear capacity that is installed, as well as the usage of the installed storage. In addition, both the export and import of electricity as well as electricity curtailment decreases the more nuclear capacity that is installed. However, as was mentioned before, the scenarios with large amounts of nuclear, that is, the Max nuclear and Autarky scenarios, had a lower usage of hydro power than other scenarios. This suggests that very large amounts of nuclear power cause hydro power to become underutilized. This could be the case in the base case of the Autarky scenario, as in this scenario, hydro power needs to be dispatched several times due to the danger of overspill. These effects may be due to import and export being heavily restricted in the Autarky scenario. It is noteworthy that in this scenario, even with a larger amount of nuclear than in the Max nuclear scenario, there is still wind and some PV installed as well. In the Max nuclear scenario, there is no curtailment at all, or storage, which means that the import and export capacity can balance the mismatch between supply and demand during the whole modeling. In general, the overproduction of electricity decreased the more nuclear power that is installed.

When analyzing the stress scenarios, the differences become even more radical than in the base scenario (Table A2). In the main, the storage requirements begin to differ even more, although the differences become smaller, and the more nuclear capacity is installed when the scenarios are compared with their basic counterparts. The differences in storage capacities can be even 10-fold when comparing normal and stress scenarios with low nuclear power capacities installed, while in scenarios with maximum amount of nuclear power, no storage was needed in neither normal nor stress scenarios. What is also of interest is that the electricity storage does not experience many recharge cycles per year, even if there is a stress scenario. This implies that the storage should be seasonal in nature.

The results of basic and stress scenarios are visualized in the graphs presented in Figure 4, assuming a nuclear lifetime of either 40 or 60 years.

Of interest are the LCOE values as well as the storage sizes, as they seem quite consistent. The following trend lines are for LCOE in basic scenarios (Equation (12a)) and for the LCOE in stress scenarios (Equation (12b)), with $r^2$-squared values of 0.9983 and 0.9973, respectively. When a 40-year technical lifetime is used, Equations (12c) and (12d) are applied. These have $r^2$-squared values of 0.9967 and 0.9977, respectively.

$$LCOE_{\text{basic}} = 3 \times 10^{-7} \times x^2 - 0.0054x + 78.537, \quad (12a)$$

$$LCOE_{\text{stress}} = 6 \times 10^{-7} \times x^2 - 0.0125x + 124.69, \quad (12b)$$

$$LCOE_{\text{basic}40} = 3 \times 10^{-7} \times x^2 - 0.0054x + 78.531, \quad (12c)$$

$$LCOE_{\text{stress}40} = 6 \times 10^{-7} \times x^2 - 0.0121x + 124.72, \quad (12d)$$

where $x$ is the installed nuclear capacity [MW] giving the specific LCOE [€/MWh].

In the stress scenarios, nuclear capacity has approximately twice as much effect on the LCOE as in the basic scenarios, when the amount of nuclear power installed is small. However, the effect of nuclear power diminishes when the installed capacity increases. In the results, this can also be seen, as the semi-max scenario has smaller LCOE than the Max nuclear scenario. When the economic lifetime is adjusted to 40 years from 60, a small change in the first-order term can be seen, which indicates that the cost decrease flattens, but not dramatically.

Similar formulae can be formulated for the required storage. These formulae are presented again for the basic (Equation (13a)) and stress scenarios (Equation (13b)). They have $r^2$-squared values of 0.9269 and 0.9991, respectively.

$$\text{Storage}_{\text{normal}} = 2 \times 10^{-6} \times x^2 - 0.0342x + 128.65, \quad (13a)$$

$$\text{Storage}_{\text{stress}} = 7 \times 10^{-6} \times x^2 - 0.1699x + 993.28, \quad (13b)$$

where $x$ is the installed nuclear capacity [MW] giving the specific storage capacity [GWh].

It can be deduced from the formulae that the first installed nuclear capacities have over five times the effect in the stress scenarios on the storage sizes than what they have in the normal scenarios. The formulae presented in Equations (12a)-(12d), (13a), and (13b) are valid only within the examined range, up to 12 000 MW nuclear capacity.

### 3.2 Effect of nuclear economic lifetime on the installed capacities

In Tables A1 and A2, a scenario called “basic 40 years” is also included. This scenario represents the basic scenario with nuclear power lifetime of 40 years instead of 60. The resulting installed nuclear capacity declined from 6315 to 5550 MW, while more wind and solar capacity was installed. This configuration, however, results in almost 50% more storage in the stress scenario than the normal basic scenario. Thus, the LCOE was stress situations almost 10% higher than in the basic scenario with a nuclear lifetime of 40 years.
Three new electricity trading scenarios were constructed. The Autarky and Medium trade scenarios were developed using the basic scenario as the starting point. However, due to the methodology used in this model, the “high trade” scenario would not have resulted in any difference when compared with the “basic” scenario in the scenario formulation. That is why the high trade scenario was developed from the “No SMR” scenario presented earlier. The results of pivoting electricity import and export capacities are shown in Table 6. The biggest effect of the electricity trading capacity is on the size of the required storage and the storage usage.

As discussed earlier, the changes in the medium trading and Autarky scenarios should be compared against the basic scenario, while the no SMR scenario should be compared against the high trade scenario. In both the medium trade and high trade scenarios, the changes affect both the size and the amount of storage cycles.
When electricity storage is larger, the amount of annual electricity storage cycles decreases. This means that the storages become more seasonal in nature as their size increases. Both increase if the size of storage is reduced. However, if the change is extreme, such as in the Autarky scenario, the capacity configuration changes dramatically and resembles the Max nuclear scenario presented earlier. However, more wind and solar are included in the Autarky scenario, as power importation and exportation are no longer available. Also, storage becomes needed in the Autarky scenario, which was not the case in the Max nuclear scenario.

### 3.4 Effect of different base year on the results

In this subsection, the basic scenario from the previous subsection was pivoted, so that the initial 2017, 2018, and 2019 historical data were replaced with only 2017, 2018, or 2019 data. The modeling was not changed in any other way. Then, new scenarios were determined with Excel Solver. The results can be seen in Table 7.

Changing the underlying historical data affects the results mainly by changing the installed wind and nuclear capacities. In addition, variations between the years are significant. In the 2019 scenario, the storage required in the stress scenario is five times larger than in the 2017 and 2018 scenarios. The effect of combining multiple years into an optimization has a larger result than using only 1 year of data. This is especially evident in Figure 6.

### 3.5 More detailed look at storage usage

Certain patterns of storage sizes can be discerned from the results presented. The power balance deficits were analyzed more closely. This refers to the values of the power balance, which were presented in Equation (2). These power balance deficits are presented in Figure 5. The power balance deficits were categorized with 250 MW intervals from 0 to 8000 MW, and graphs are plotted between these points.

As Figure 5 shows, there are significant differences between the scenarios, but a similar trend prevails...
between panel A and panel B. In stress scenarios, the power deficits are both more numerous and greater than in the normal scenarios, but both the number of hours with power a deficit and their magnitude decrease both in normal and stress scenarios when more nuclear power is introduced. Panel C suggests that the 2019 data produce the greatest power deficits, but still the scenario with historical data from all three different years has the greatest number and magnitude of power deficits by a wide margin. In panel D, increasing electricity trading can be seen to have a similar effect on the power deficits as increasing nuclear capacity. The only exception is the Autarky scenario, which has the smallest trading capacities, but still the least amount of deficit. This can partly be explained by the very large amount of nuclear capacity installed in the Autarky scenario, which has power deficits, while the max nuclear scenario in panel B does not. The behavior is, therefore, consistent, as these scenarios have a similar amount of nuclear capacity but reducing electricity trading has increased the power deficits. The general shape of panels presented in Figure 5 points to another behavior, which is the durationally short but very deep power deficit, a behavior which was evident in all scenarios that needed power storage. Figure 6 shows the hourly charge in the electricity storage of the No nuclear stress scenario, which is the scenario with the greatest power deficits. Here, the rapid depletion of the electricity storage due to a very high but durationally relatively short power deficit is evident.

During the data year 2018, at around the modeled hour of 10 000 (of the three-year period), the electricity storage is depleted quickly. At all other hours, the storage is not even close to being empty. A system that is optimized for a range of years could result in a significant power deficit during a single year. This has clear implications for system availability. If a system designed with only a single year's available data that are subjected, especially in a stress scenario, to the 3 years of historical data, it will lead to system unavailability and an infeasible solution, as the storage non-negativity constraint from Equation (11) is violated. This is a similar behavior as was noted in Reference 24 where in high-VRE scenarios, utilizing only single weather year in the system design led to unmet demand in significant number of hours when the weather year was changed.

**TABLE 7  Effect of base year**

| Scenario                        | All years | 2017 | 2018 | 2019 |
|---------------------------------|-----------|------|------|------|
| Wind capacity [MW]              | 25 408    | 16 713 | 16 284 | 14 766 |
| Solar capacity [MW]             | 1246      | 1259 | 1109 | 1112 |
| Nuclear total [MW]              | 6316      | 7906 | 8131 | 7880 |
| Storage [GWh]                   | 0         | 0    | 0    | 0    |
| LCOE [€/MWh]                   | 57.39     | 56.89 | 57.47 | 54.97 |
| Production of wind (TWh/a)      | 64.54     | 39.15 | 42.96 | 38.97 |
| Production of solar (TWh/a)     | 1.15      | 0.95 | 1.08 | 1.15 |
| Production of nuclear (TWh/a)   | 52.44     | 65.68 | 67.55 | 65.46 |
| Production of hydro (TWh/a)     | 11.76     | 11.76 | 11.76 | 11.76 |
| Production of black liquor (TWh)| 5.34      | 5.34 | 5.34 | 5.34 |
| Export (TWh/a)                  | 23.43     | 17.68 | 21.65 | 17.80 |
| Import (TWh/a)                  | 2.30      | 1.19 | 1.45 | 1.51 |
| Curtailment (TWh/a)             | 9.10      | 1.40 | 3.48 | 1.38 |
| \(P_{\text{cap,normal}}\) [MW] | 1594      | 1628 | 1823 | 1592 |
| Storage stress [GWh]            | 220       | 27   | 23   | 114  |
| LCOE stress [€/MWh]             | 69.42     | 58.73 | 59.10 | 61.34 |
| Production of hydro stress (TWh/a)| 7.08    | 7.08 | 7.08 | 7.08 |
| Export stress (TWh/a)           | 13.36     | 11.13 | 13.07 | 10.95 |
| Import stress (TWh/a)           | 4.83      | 3.49 | 3.29 | 3.63 |
| Curtailment stress (TWh/a)      | 16.88     | 5.56 | 9.22 | 5.62 |
| Annual electricity storage cycles| 2.22      | 1.88 | 2.26 | 1.98 |

\( \text{aSame as basic scenario in other tables.} \)
FIGURE 5  In these panels, the number of hours where a power balance deficit presented on the X-axis is exceeded is presented. The values presented are cumulative, that is, all values, which are at 500 MW, are also included at 0 MW. A, The power balance deficits, that is, in normal nuclear scenarios. B, The power balance deficits in stress nuclear scenarios. C, The storage usage in stress scenarios, with different years data. D, Power deficits in stress scenarios with different trading values.
3.6 | Hydro usage

There were differences in hydro usage, even if for the majority of the scenarios, the hydro usage during the normal and stress scenarios was the same. During stress scenarios, in most of the scenarios, the hydro usage in normal situations had to be limited. The only scenario where this did not occur was the Autarky scenario stress test. On the contrary, even without any limiting, the hydropower remained underused in this scenario, indicating that there was excessive generation for most hours. In Figure 7, the hydro reservoir is shown for the basic and Autarky scenarios.

As is evident from Figure 7, the limitation of hydro usage in normal situations makes the hydro reservoir much flatter. In general, in all stress scenarios, hydropower dispatch was radically reduced. However, this was not the case in the Autarky scenario, due to the reduced need to dispatch hydro even during a stress scenario. The issue in stress scenarios is generally the hydropower capacity, as it is insufficient to balance out the variations in variable generation in the short term. In addition, overall reservoir usage was a concern in all stress scenarios except the Autarky scenario.

4 | DISCUSSION

4.1 | Hydro modeling and dispatchment

The hydrological inflows in this model are based upon historical data. Therefore, the impacts of climate change should also be considered if modeling for 2050. Climate change especially affects the seasonal distribution of discharges and hydro power generation, with increases during winter and decreases during summer. In addition, the hydro dispatchment in this model is only based on the hourly power balance, and at stress scenarios, the hydropower dispatchment needs to be curtailed in order to not dispatch too much hydro. In this study, a change was made to previous models, when the full hydro capacity was allowed to be dispatched for the worst hours. This has a significant effect on storage requirements. For example, in Reference 27 in a similarly formulated basic scenario stress test, a storage of 300 GWh was required, whereas in this modeling, the storage needed was 220 GWh. Therefore, it can be assumed that if the dispatchment was done in an even more optimized way, the storage requirements could be even smaller, provided that other hydropower assumptions made in this work remain the same.

4.2 | Electricity storage considerations

Electricity storage displays certain seasonal tendencies. This can be seen in particular in the low average annual cycle amounts, which in most scenarios was around two, and at most around four. A distinct feature of the storage was also that the storage was rapidly used within a short amount of time, while for most of the time, the storage remains full. This behavior was already reported in Reference 27. A solution to this problem could be to change the electricity storage technology to a seasonal one, as
currently the technology used is battery storage. An alternative technology such as compressed-air energy storage (CAES) could be considered. However, the used battery costs are so low, that replacing the used costs with reported PHS costs, which are even lower than the lowest CAES costs, and the most optimistic CAES lifetimes reported in Reference 47 of €600 000/MW and a 40-year lifetime result in the No nuclear scenario, for example, having an LCOE of €118.95/MWh compared with €78.39/MWh with the battery costs and lifetimes assumed in this work. Alternative solutions to storage should be explored to address the very sharp power deficits, such as introducing additional technologies during the most severe deficits, or alternatively converting curtailed energy into usable feedstocks to be used during peak consumption hours via power-to-x technologies, or the inclusion of demand side management, as it has been found to be an efficient mean to integrate renewable energy sources (RES), and reduced the need for cross-border electricity balancing.48,49

The lack of flexibility within the system may cause these very large peaks to appear, which then dominate the results of the electricity storage, and cause the storage to have seemingly seasonal behavior. Indeed, if the largest drops in the storage in Figure 6 are left out of consideration and only the highest 100 GWh or so of the electricity storage level is analyzed, as has been done in Figure 8, the profile of the electricity storage changes to include many more charge and discharge cycles.

4.3 | Effects of nuclear capacity on storage and model configuration

Increasing nuclear capacity decreases the required storage, installed wind capacity, and LCOE (Tables A1 and A2). Solar capacity remained quite constant at around 1200 MW. A larger amount of nuclear energy decreases the curtailment need. In the scenarios with lower or no nuclear capacity at all, very large amounts of wind power were installed, with significant curtailment as well. For example, in the No nuclear scenario, electricity demand was 105 TWh/a, wind power production 181 TWh/a, and 61 TWh/a curtailed. Due to periods of low wind, larger amounts of storage are needed, which increases LCOE. However, nuclear capacity beyond 9050 MW increased the LCOE. Including nuclear power in an otherwise highly renewable power system has been found to decrease costs by 30% in the literature.14

4.4 | Effect of electricity trading capacity

Improving electricity trading capacity obviously decreases the need for both storage and generation capacity. The costs of connections are a small fraction of the savings. This is especially evident when no SMR and High trade scenarios were compared. However, when electricity trading is heavily restricted, the resulting system uses all available technologies as well as storage. As no external balancing is available, more internal production is utilized, as it is still more cost-effective than simply larger amounts of nuclear power. As this type of behavior was evident only in the Autarky scenario, in future research, electricity trading needs to be implemented as a dispatchable resource, which results in both revenue and expenditure. With this type of implementation, the resulting scenarios would be more realistic and would have additional costs related to importing electricity, which could additionally push the modeling results toward Autarky-like scenarios, where all technologies are utilized, without having to curtail produced electricity too much.

4.5 | Effects of modeling year on storage and model configurations

The modeling period was found to significantly influence both storage and installed generation capacities. The scenario with all years used had the largest amount of storage in the stress scenario. It points to a phenomenon where the increased variability of the data could itself contribute to the size of the storage. This reinforces the finding that to build a reliable model, several years of data need to be considered. There seems to be a mismatch between these scenario results and the storage usage in Figure 6, where the electricity storage is depleted during the second modeled year, which corresponds to historical data from 2018. In the scenario results, the
scenario constructed using historical data from 2019 had the greatest need for storage. The reason for this mismatch is not directly evident, as the installed capacity configurations are also different, influencing the required storage sizes. This warrants future research and could be approached by producing various wind, PV, and demand, scenarios, for example, instead of just relying on purely historical data. The variability in the historical data is higher when all years are included, which could decrease the optimality of the results. This might also explain some of the behavior. A similar conclusion was reached in Reference 20, where varying the base year caused energy costs to vary by up to 10%.

5 | CONCLUSIONS

This work examined the contributing factors to the need for electric storage in a carbon-free Finnish power system, which only included a minimal amount of combustion. The modeled carbon-free power system contained multiple unusual features in international comparison, such as hydropower being the only adjustable electricity generation source, high electricity import, and export capacities, as well as highly restricted usage of different generation technologies. In Finland, hydropower is an important balancing power technology, and nuclear power is an important baseload technology. The proposed carbon-free power system emphasizes these roles even further. In addition, the large share of nuclear power is rare in international comparison.

This system was studied with thoroughly assessing different hydrological scenarios for different modeled years. The model included both import and export of electricity, which provided additional flexibility for the model.

Hydropower was subjected to stress scenarios due to its importance in the model, by introducing exceptionally dry years based on detailed hydrological modeling. The model featured a three-year period of historical data, and a multitude of scenarios where the amount of nuclear power and electricity trading and the used historical data were modified. This was done to investigate their impact on the behavior of the electricity storage. This specific type of configuration was not found in the existing literature.

It was found that nuclear capacity contributed by lowering the required storage capacity. In addition, nuclear capacity reduced the curtailment of electricity, thus resulting in a more efficient power system. These findings could be significant when designing other systems with high shares of renewables. An increase in electricity trading capacity was also found to reduce the need for electricity storages. This was consistent with the general observations made from the literature review in Section 1.3. However, as was evident from the Autarky scenario, it would also be possible to design a carbon-free power system with severely reduced electricity trading, but this would result in hydropower being underused as a flexibility resource.

The used historical data also contributed to the use of the storage, as the scenario utilizing only 2019 data was found to have a much higher required storage capacity than scenarios utilizing data from other years. The inclusion of data from multiple different years was found to increase the required electricity storage capacity when compared to scenarios with only 1 year of data. This is an important observation, as it suggests that system availability could be endangered, if only a single year of data is used as a base year. This suggests that the model presented considers the renewable variability well and takes the interannual variability into account, thus increasing the reliability of the model.

The use of electricity storage was found to exhibit mainly seasonal behavior within this model, but this was possibly due to the lack of demand flexibility within the model. However, this could also reinforce the findings from the literature, suggesting that seasonal storage is more important than medium- or short-term storages at the system level. As some of the other models were capacity expansion models, they introduced flexibly dispatchable power generation technologies, such as biomass, which could be considered in the future. However, these flexible power generation technologies would increase the amount of combustion used in power generation dramatically. Additional carbon-free flexibility could be introduced to the model via the deployment of demand response (DR).

However, the reader should note that the large-scale electricity DR of private consumers and small- and medium-sized industry in Finland has progressed rather slowly. As of 2018, a 1 MW “virtual battery” had been achieved by aggregating electric heating of small consumers, and DR and uncertainties in profits achieved from DR projects have reduced the willingness of grocery stores, for example, to invest in such projects.50

In future research, the general power dispatch of the model should be expanded to add more flexibility. Alternative balancing sources and flexibility in general in addition to battery storage, that is, power-to-x or other technologies, were implemented in the studies found in the literature survey and as well as DR, as DR has been estimated to carry significant potential in References 48 and 49. Implementing more wind power and demand scenarios could allow the further investigation of the effects of varying data. In addition, more regions could be
added to the power system, to further optimize the effectiveness of renewable energy deployment. Inclusion of a broader range of firm low-carbon electricity resources, such as natural gas with carbon capture and storage, could also be considered, as this has been found to decrease costs in zero carbon emission scenarios significantly. This could mean relaxing the carbon-free part in the study, but carbon usage could be set as a scenario parameter.

CONFLICT OF INTERESTS
The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

AUTHOR CONTRIBUTIONS
Tero Koivunen: Conceptualization; methodology, overall; software; validation; investigation; data curation; writing—original draft preparation; visualization. Sanna Syri: Conceptualization; resources; writing—review and editing; supervision; project administration; funding acquisition. Noora Veijalainen: writing—Section 2.5.1; writing—review and editing. All authors have read and agreed to the published version of the manuscript.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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APPENDIX

TABLE A1  Basic scenario results

| Scenarios                  | No nuclear | Hanhikivi | Olkiluoto | No SMR | Basic | Basic 40 years | Semi-basic | Semi-max | Max |
|----------------------------|------------|-----------|-----------|--------|-------|---------------|-----------|---------|-----|
| Wind capacity [MW]         | 71 245     | 62 922    | 59 951    | 51 285 | 25 408| 30 039        | 16 439    | 8582    | 8   |
| Solar capacity [MW]        | 1405       | 1129      | 1183      | 1190   | 1246  | 2110          | 993       | 1228    | 0   |
| Total nuclear capacity [MW]| 0          | 1200      | 1600      | 2800   | 6316  | 5532          | 7675      | 9050    | 11 645 |
| Storage [GWh]              | 153        | 82        | 66        | 31     | 0     | 0             | 0         | 0       | 0   |
| LCOE [€/MWh]               | 78.39      | 72.41     | 70.70     | 66.47  | 57.39 | 60.39         | 55.48     | 54.84   | 58.52 |
| Wind [TWh/a]               | 181        | 160       | 152       | 130    | 65    | 76.3          | 42        | 22      | 0   |
| PV [TWh/a]                 | 1.30       | 1.04      | 1.09      | 1.09   | 1.46  | 1.94          | 0.91      | 1.13    | 0   |
| Nuclear [TWh/a]            | 0          | 9.94      | 13.2      | 23.2   | 52.4  | 46.1          | 63.8      | 75.2    | 96.8 |
| Export [TWh/a]             | 32.7       | 31.9      | 31.5      | 30.4   | 23.4  | 25.25         | 18.2      | 11.4    | 9.4  |
| Import [TWh/a]             | 74.8       | 64.4      | 6.06      | 4.95   | 2.30  | 2.73          | 1.68      | 1.20    | 0.45 |
| Curtailment [TWh/a]        | 69.1       | 57.4      | 53.2      | 41.2   | 9.10  | 13.9          | 1.96      | 0.06    | 0   |
| Annual electricity storage cycles | 1.72   | 1.45      | 1.32      | 0.88   | -     | -             | -         | -       | -   |

TABLE A2  Stress scenario results

| Scenarios                  | No nuclear | Hanhikivi | Olkiluoto | No SMR | Basic | Basic 40 years | Semi-basic | Semi-max | Max |
|----------------------------|------------|-----------|-----------|--------|-------|---------------|-----------|---------|-----|
| $P_{\text{hcap.normal}}$ [MW]| 1751       | 1739      | 1732      | 1713   | 1594  | 1625          | 1555      | 1556    | 1631 |
| Storage [GWh]               | 991        | 811       | 721       | 586    | 220   | 318           | 101       | 45      | 0   |
| LCOE [€/MWh]                | 122.72     | 111.06    | 106.94    | 96.01  | 68.79 | 77.63         | 61.16     | 57.60   | 58.52 |
| Export [TWh/a]              | 16.6       | 16.4      | 16.3      | 16.0   | 13.4  | 14.1          | 11.2      | 8.10    | 6.47 |
| Import [TWh/a]              | 7.32       | 7.06      | 6.92      | 6.50   | 4.83  | 5.13          | 4.22      | 3.60    | 2.25 |
| Curtailment [TWh/a]         | 79.4       | 68.1      | 64.0      | 52.0   | 16.9  | 22.6          | 6.77      | 1.04    | 0.01 |
| Electricity storage cycles per year | 4.19   | 3.82      | 3.84      | 3.21   | 3.22  | 2.19          | 2.07      | 1.03    | -   |