Energy Simulator

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Bachelor's thesis
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Abstract of the bachelor's thesis

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Abstract
The Finnish electricity market is experiencing multiple simultaneous challenges, as its heavy reliance on cheap electricity imports from Sweden and Norway is likely to become challenged due to reduced Swedish production capacity and increased prices due to increased sales of Norwegian electricity to Central European markets. Simultaneously Finland needs to meet the greenhouse gas emission reduction goals of the EU and the Paris accord. The increased capacity of renewable energy such as wind and solar power also poses challenges due to their high production variability.
While, at this time, Finland needs to define a comprehensive energy policy to meet these challenges in the decades, the general public is increasingly polarized and sceptical on energy policy issues. If unchecked, it has a possibility of hindering rational and holistic debate on the energy policy, thus potentially delaying Finland's response to CO_2 reduction targets, and even threatening the security of electricity supply in Finland.
This thesis work presents an energy simulation game as a way to educate the general public on the complexities of Finland's energy policy. The simulation allows users to enact their own energy policies and immediately see the results on security of supply and greenhouse gas emissions.

Keywords Energy policy, simulation, gamification, Finnish electricity market

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Preface

I wish to thank the supervising professor Filip Tuomisto for accepting my unorthodox proposal for Bachelor's thesis work. The work on researching Finnish electricity market and having to practically work on constructing a working model from the raw data has been a very enlightening experience. My thesis advisor, Jarmo Ala-Heikkilä was an invaluable source of information, comments, and support during this work. Maurice Forget and Tuomas Paloposki from the AAN-C2008 Research Project course provided the constant prodding-on and feedback to keep the work rolling, for which I am grateful. I also wish to provide my thanks to Taina Kurki-Suonio and Sanna Syri from Aalto University, and Heikki Raatikainen from Fingrid who all helped me researching the required data. Finally, Päivi Oinonen from Aalto Design Factory and all of the other students on the research course offered feedback on the Energy Simulator game during its development.

Otaniemi, 15.12.2017

Santeri Paavolainen

Contents

1 Introduction

Energy policy can be defined as the set of governmental policies that affect the production, consumption, and transmission of energy. Energy policies can have impact on the environment, economy, and society. Energy policies are implemented by governments through a variety of means, including taxation, subsidies, and regulation. Energy policies also reflect each country's geography, and availability of natural resources such as coal. Political movements such as the green party have an influence on energy policies. Energy policies also need to take into account neighbouring countries policies, and even consider the possibility of electricity exports being used a geopolitical tool. Since the use of energy, including electricity, permeates all aspects of daily life in most western societies, energy policies clearly can have a wide-ranging effect on all of society.

A recent study by Pitkänen and Westinen on the attitudes of the Finnish general public towards energy policies [1] showed that, for example, positive attitudes towards urbanization highly correlated with negative attitudes towards the use of wood as an energy source and vice versa. This polarization is at odds with most Finnish energy experts who observe the need for multitude of different approaches towards the future of Finland's energy production and consumption [2, 3, 4]. Since energy policies are by definition defined by the government, they are intrinsically also part of the political process, and eventually also affected by the public opinion. It is thus possible that unnecessary polarization or biases in the energy policy discussion can influence future energy policies in undesirable ways. Therefore, keeping the general population informed and knowledgeable about the complexities of energy policy is a solid foundation for rational public debate on the issue.

The availability of energy — either as heat, or more specifically, electricity — is an important factor in the everyday quality of life. The availability and quality of electricity is an important part of Finland's economical environment. The security of electricity supply in Finland has historically been good on account of power outages being rare and other quality degradations (such as undervoltages and frequency fluctuations) are virtually nonexistent. In 2016 the average number of outages in Finland per electricity customer was 6.3 per year with the average total outage duration of 2 hours 6 minutes [5][1]. The majority of electricity quality issues in Finland are due to trees falling on overhead transmission lines. Consequently in 2013 the government enacted regulations requiring local power utilities to increase transmission reliability, effectively requiring increased deployment of underground power lines [6, 7]. Thus it can be deduced that the quality of Finnish electricity transmission networks is already satisfactory and likely to accomplish increased reliability in the near future.

In contrast, the safety of electricity *production* is not as good. During 2016 Finland imported 22.3% of its electricity from Sweden, Norway, Estonia and Russia. Notably, during January the same year Finland experienced a record instantaneous electricity demand of 15 177 MW. At this time imports were at a high level of 4 328 MW with almost 1 500 MW from Russia [8]. The last fact highlights a potential problem on Finland's security of electricy supply as Russia is known to employ its energy exports as a geopolitical tool [9]. Even if the geopolitical risks are disregarded, Finland's heavy dependence on

[1]The averages are higher than for example in France due to the higher proportion of Finnish population living in rural areas. Electricity quality is higher for municipal residents in Finland, too.

imports is troubling when the reduction of electricity production capacity in Sweden and expansion of Norway's energy sale market are taken into account. Sweden will decommission 2 326 MW of nuclear power within the next decade[2]. Transmission lines with a total capacity of 2 800 MW are being built from Norway to the United Kingdom and Germany, which are expected to raise electricity prices in the Nordic area [10]. The record peak demand of January 2016 is not an immediate concern regarding the security of electricity supply [11], it is also clear that current and future energy policies will have impact on Finland's future energy safety.

Finnish energy production faces numerous changes and challenges in the future. The Olkiluoto 3 nuclear power plant should be commissioned in 2019, adding 1 600 MW of production capacity. Hanhikivi 1 nuclear power plant, potentially in operation during mid-2020's, would add another 1 200 MW of electricity production. While not certain, it is likely that the existing trends in power production continue — between 2013 and 2016 the wind power production capacity increased by 1 080 MW[3], and in the same period electricity production from coal dropped by 25% [8]. While solar power production in Finland is still quite low, it is similarly expected to increase. Unlike other production methods, wind and solar power variability is high, which may lead to lower quality of electricity. For example, the increased use of renewables has lead to changes on how nuclear energy is used as has occurred in Germany [12]. All taken together, it can be seen that a successful energy policy in Finland cannot be based on just "adding more of *some type of production*".

However, attitudes can be changed. *What could be done to bring more nuanced views to the discussion?* A typical approach is the use of "expert opinion", but it is doubtful whether it would have any kind of impact. There is push-back against experts in Finnish popular politics [13], and a bachelor's thesis is not likely to be viewed as a significant contribution regardless. An alternative approach is to avoid "teaching" and instead create a situation where learning occurs. For this purpose "gamification" can be used to create such a situation where people through the act of performing an interesting task (e.g. play a game) gain insight into the underlying problem. To this end, the work described in this report aims to produce an interactive, sandbox simulation of the Finnish electricity market. The player of the "game" can enact their own energy policy and play "what-if" scenarios. The simulation will produce immediate results showing the relevant information on energy safety and greenhouse gas emissions.

The following sections describe the Finnish energy market in more detail (Section 2) and its use to model the Finnish energy market (Section 3). Details on the parameters used for simulation model and their correspondence to the real Finnish electricity market is detailed in Section 4. The Monte Carlo simulation of the model is briefly described in Section 5, with conclusions and closing remarks in Sections 6.

[2]Ringhals R2 will be decommissioned in 2019, and Ringhals R1 and Oskarshamn O2 in 2020.

[3]The actual production depends on winds, and over the whole year in is Finland about 20% of the theoretical maximum.

2 Background

2.1 Terminology

It is important to be aware of the correct terminology and notation when discussing energy and electricity. While **energy** is measured in *joules* in SI units, for electricity a more common unit of energy is the *kilowatt-hour* (kWh), commonly found in electricity bills. A kilowatt-hour is sufficient for domestic use, although on a country level terawatt-hour (TWh, 10^{12} watt-hours) is a more useful unit of electric energy.

The SI unit for **power** is a *watt* (W). A typical power plant has a maximum production capacity of a few hundred megawatts (MW). Power is an instantaneous unit without a time dimension, therefore when attention in discussion needs to be drawn into the fact that the production capacity (power) is an averaged measurement an alternative notation of watt-hours-in-hour (Wh/h) is frequently used — technically both are equivalent, but this notation offers a contextual hint to the reader.

A **capacity factor** describes in unitless terms the ratio between actual, measureable energy production of a power plant to its theoretical maximum output during a time period. For most types of power plants the capacity factor reflects combination of plant's reliability, maintenance, and demand for the plant's production output. For renewables such as wind and solar this additionally includes effects of local weather, as well as predictable daily and seasonal variations.

For CO_2 emissions a typical unit of measure is either the amount of emissions per energy production, often in units of grams per kilowatt-hour (g/kWh, which is equivalent to tonnes/MWh). A more suitable unit for measuring CO_2 emissions of a country over a year is megatonnes (millions of tonnes, Mt). The unit often used in regulation of greenhouse gas emissions is CO_2-equivalent (CO_2eq), frequently expressed as *tonnes of* CO_2 *equivalent*. The CO_2eq includes contributions from gases other than carbon dioxide (CO_2) such as methane. In this work CO_2 and CO_2eq are more or less on equal footing as the majority of direct greenhouse gas emissions from a power plant are pure CO_2 emissions. This work does not take lifecycle emissions into account, which would include emissions from mining and transport of fuels, for example.

Finally the reader should be aware of the different of **baseload** and **load following** power generation. Power plants operating as baseload generation are run at full production capacity, whereas load following plants adjust their production continuously based on the instantaneous demand for electricity and thus run at less than their full production capacity. Since a large portion of the daily and seasonal electricity variation is predictable, grid operators satisfy this predictable variation by bringing baseload power stations online and taking them offline, while more rapid demand variations are managed by load following plants.

2.2 Finnish electricity market

The Finnish energy production market is highly privatised with the government holding no direct control over or ownership in most energy companies. The Finnish energy policy is enacted through taxation and subsidies, with regulations mainly focused with environmental issues and operational safety. The construction and operation of power plants is subject to commercial market forces, with the price of electricity being the main determining factor on investments[4]. The main national grid is controlled by the government through majority holdings in Fingrid, the company responsible for the main grid. While local grids are privately owned, they are heavily regulated on factors such as service quality and transfer pricing.

Finland is part of the Nordic electricity market formed by Denmark, Estonia, Finland, Latvia, Lithuania, Norway, and Sweden. Consequently the wholesale electricity price in Finland is determined by the supply and demand over the whole Nordic region and the Baltics. Finland has grid connections to Estonia, Norway, Sweden, and Russia. The price and availability of Russian electricity imports are set by a bilateral agreement separately from the Nordic electricity market. The surplus of low-cost electricity from Norway and Sweden (hydropower and nuclear power) has historically been beneficial to Finland, and consequently has kept the price of electricity in Finland low relative to the EU average (0.155 €/kWh and 0.205 €/kWh respectively in 2016, for domestic customers [14]). The low wholesale electricity prices, in conjunction with the long-overdue Olkiluoto 3 nuclear power plant project has depressed energy investments, leading to reliance on imported power. Jääskeläinen et al estimated that during the January 2016 demand peak of over 15 GW there was only an estimated 11.6 GW of domestic production capacity available [11].

The total yearly electricity use in Finland in 2016 was 85.1 TWh, with the largest portion being produced domestically through nuclear power and hydro (26.2% and 18.4% respectively), with imports comprising over one-fifth of the electricity usage at 22.3% (see Figure 1). Finland's electricity use peaks during the winter and is lowest during summer with about 7 TW difference in from lowest to highest average power demand (see Figure 2).

Finland has to meet the European Union's goals for greenhouse gas emission reductions of reducing CO_2eq emissions by 39% from their 2005 level (68.7 Mt CO_2) before 2030. The EU goals also include demands to increase the use of renewable energy sources. Finland's greenhouse gas emissions have been in decline, and in 2016 they were estimated to be 58.8 million tonnes CO_2eq [15], with electricity production accounting for 7 Mt CO_2 [8].

[4]Nuclear energy is the exception, as building of a nuclear power plant requires a parliamentary decision.

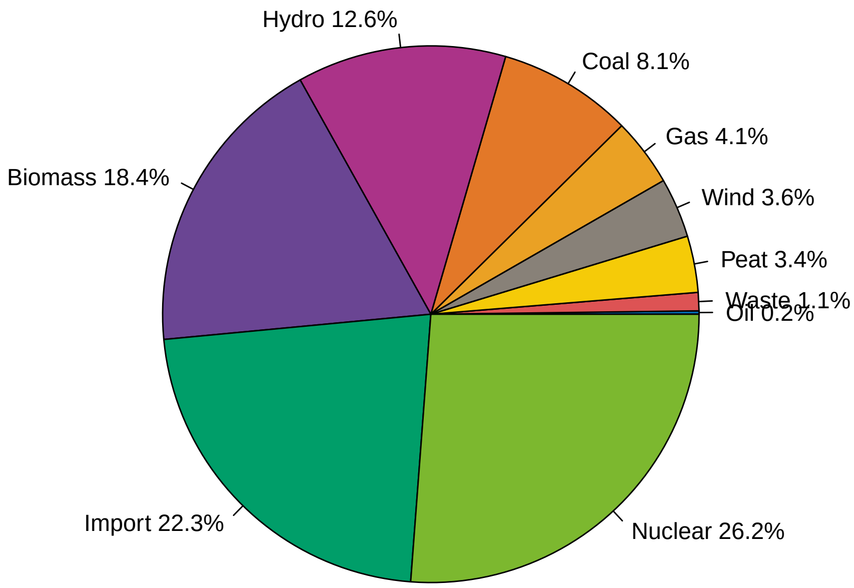


Figure 1: Finnish electricity use in 2016 categorized by the energy production method (adapted from [8])

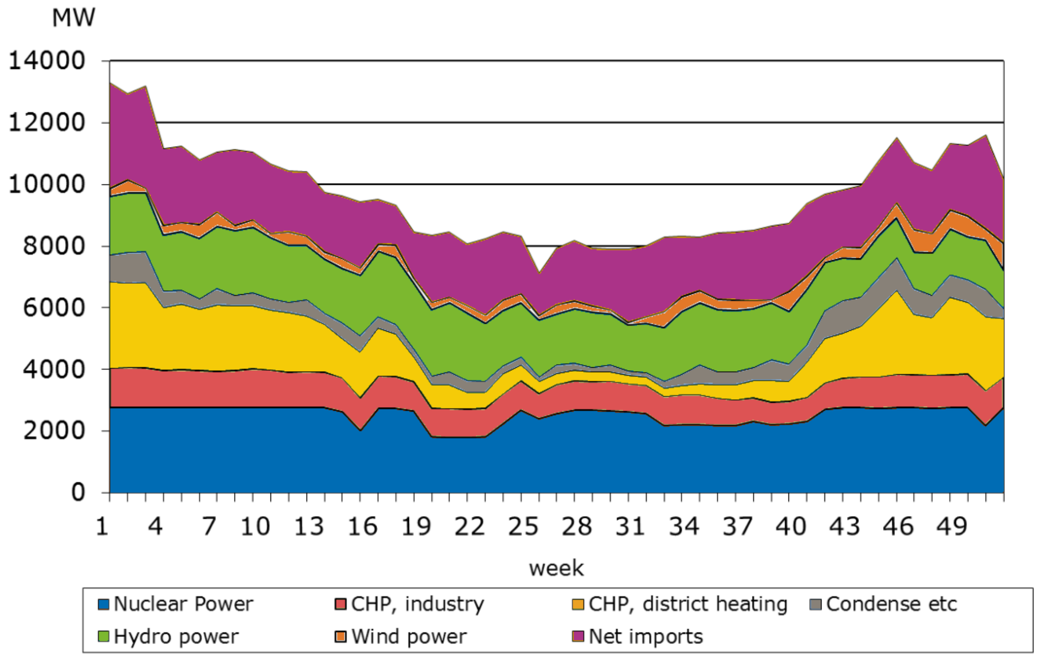


Figure 2: Variation of electricity demand and supply in Finland during 2016 (from [8])

3 Model

3.1 Overview

For the simulation a model of Finland's electricity production, consumption, and transmission was constructed. This model is highly simplified to make it computationally lighter to make it fast enough to be run on a browser interactively, to simplify modeling itself as many model parameters are aggregated over the whole area, and to make the model simple enough for the user to be mentally able to conceptualize and manipulate the model. Specifically, the model consists of:

- **Areas,** which depict geographically separate regions that are parameterized by their electricity sinks (demand), sources (production), and transmission capabilities.
- **Lines** describe transmission capacities between different areas, characterized by their maximum transmission capacities and transmission models.
- **Sinks** describe the electricity demand of an area ("negative production"), and are characterized by demand models.
- **Sources** are electricity production units and are characterized by production models and greenhouse gas emissions in CO_2 t/MW.
- **Transmission, demand, and production models** describe the power transmission capacity, demand, or production capacity as a probability distribution (these are described more in detail in Section 3.2).

The model for Finland comprises of five areas (south, east, west, center, and north[5]) with transmission lines between neighbouring areas. All electricity producing plants within an area are aggregated by their fuel type (coal, biomass, wind, etc.) into a single source. Neighbouring countries are modeled as separate, external areas, and are linked to appropriate Finnish areas with a transmission line of the known maximum transmission line capacity. You can see a graphical depiction of this model in Figure 3.

3.2 Capacity models

Transmission lines, demand, and production units all are associated with a *capacity model*. A capacity model defines the probability that the unit at any moment has a given *capacity*. Formally defined, a capacity model is a probability density function $P(C)$ of capacity C. The model of Finland uses *normalized* discrete probability $P(\hat{C})$ that then is used with the nominal capacity P_{unit} to calculate the actual unit capacity $\hat{C} \cdot P_{\text{unit}}$. For an example, see Figure 4 showing the normalized distribution for demand and the normalized distribution for wind production.

Capacity models P are either *aggregated* or *independent*. These differ in how they are sampled during simulation. Aggregated models are sampled only once (and the sampled

[5]The choice of areas was arbitrarily based on how many areas were considered to be manageable for an user of the simulation.

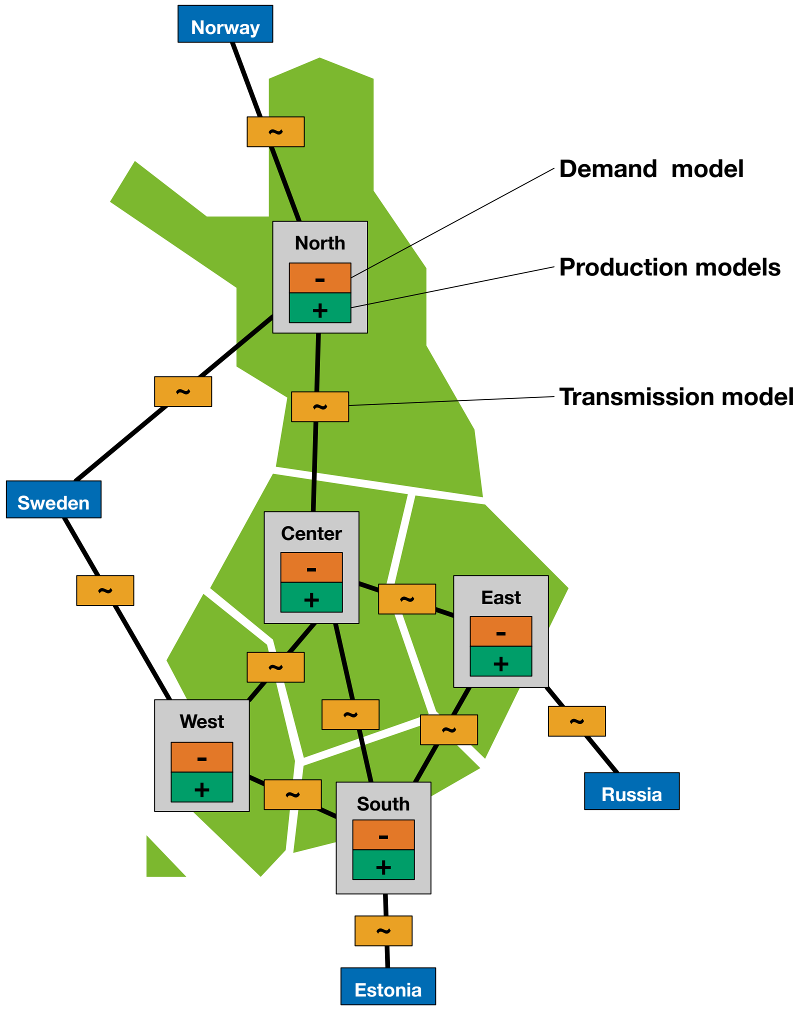


Figure 3: Model of Finland including transmission lines from neighbouring countries for electricity import. The continuous boundary shows areas that make up “Finland” in this model. Production models for neighbouring countries are not shown as the international transmission lines are the limiting factor.

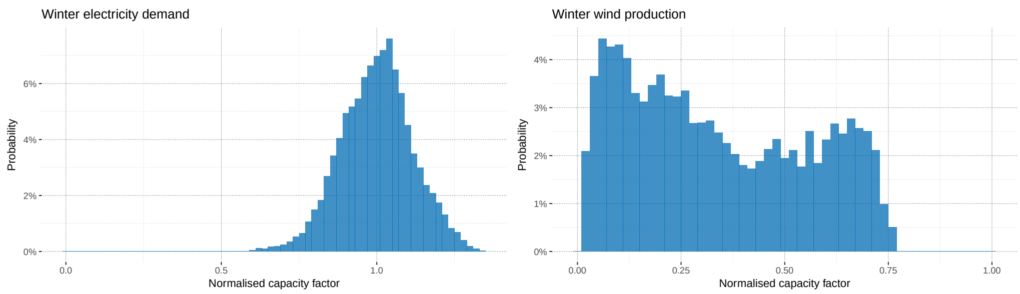


Figure 4: Capacity models for Finland’s winter electricity demand and wind production. Capacity factor is a normalized unit with its semantic meaning defined by the context. For example, for demand capacity model $\hat{C} = 1.0$ is the average demand, where $\hat{C} > 1.0$ reflect the probability of demand being over the average. For wind production the upper limit $\hat{C} = 1.0$ is the maximum capacity of Finland’s wind power.

value is re-used) during each simulation round whereas independent models are sampled every time a $\hat{C}$ is needed for an unit. This distinction is required as several of the data sources for capacity model generation are already aggregated over the whole Finland, and sampling the distribution more than once would suppress variance of the results (see the central limit theorem in statistics). For example the Finnish electricity demand distribution in Figure 4 is generated from data that aggregates the demand of the whole Finland. Individual capacity models and their parameters are discussed in detail in Section 4.

The use of capacity models allows the simulation to account for natural variations in demand and production due to time of day and temperature as well as unexpected failures. For aggregated models, failures are assumed to be already statistically represented in the original sample. Models can also be interpolated from failure data, or extrapolated using reliability information from literature or research.

3.3 Limitations

Due to practical reasons, this model and the simulation using the model include a large number of significant simplifications. Nonethless, these simplifications have been made in a manner that tries to retain an amount of realism to keep the simulation relevant for the purpose of this work. The various simplifications and limitations are described below.

Lack of electricity pricing

This model does not include electricity prices. Electricity pricing has been mainly omitted due to practical purposes to reduce the amount of work. The price of electricity is also subject to market and political forces. Finally, while Finland is likely to face increases in electricity prices, any impacts on demand and production are exactly those decisions the user is asked to perform in this game.

Issues with CO_2 attribution on imported electricity

Within the context of the Paris accord and EU's CO_2 reduction targets any emissions from electricity production are counted against the country where the electricity is produced — not against the country where it is *consumed*. Consequently, in the short term countries are able to artificially lower their CO_2 emissions by relying on imported electricity. In the long run, it is expected that CO_2 reduction actions will be reflected in electricity prices which in turn may make national low-CO_2 production methods more attractive as investments. This feedback loop is missing as the model does not include pricing.

Unrealistic prioritisation of hydropower

Safety of electricity supply is potentially reduced due to attempts made to meet the greenhouse gas emissions targets — if CO_2 emissions were not an issue, either building new or refurbishing existing coal-firing power plants would be an easy solution[6]. Secondly, future

[6] A large portion of Finland's reduction in electricity production capacity has been from decommissioning of coal power plants.

electricity prices are expected to increasingly include costs due to CO_2 emission taxation and/or subsidies of low-emission alternatives. To this end the simulation prioritizes low-emission production methods. For most production methods this has few consequences, as the low-emission methods are either used as baseload power (nuclear), or all available production is used regardless (wind, solar). Nonethless, the simulation does significantly differ from reality in the case of hydroower. Hydropower has low CO_2 emissions so this model will preferentially use it over gas or coal, for example. Yet in Finland hydropower is primarily used for load following operations. Thus, predictable demand increases would be primarily met from baseload generation and not by hydropower. The added baseload generation power would primarily be coal and gas power plants, thus keeping the hydropower in load following mode.

Thus in Finland it is possible to have coal fired power plants in electricity generation even when there is unused hydropower capacity. This is not handled in this model, and as a result the CO_2 emission calculations are likely to be underestimates.

Lack of time dimension

The simulation has no history and is able to model only instantaneous, discrete steps. The lack of history (e.g. time) prevents the simulation to represent short-term changes in demand and production capacities. Large short-term demand changes can lead to electricity quality issues or even brownouts as the power plants operating in load following mode have a limited speed, e.g. *ramping rate* at which they can increase or reduce their power generation. Increasing wind and solar power connected to the main grid increases the need for load following capacity [12]. By modeling temporal electricity demand changes it would be possible to evaluate whether the grid has enough ramping capacity to respond to the changes.

Lack of seasonal variation

The parameters used for the model are based on wintertime demand and production capacity. This allows the model to be used to evaluate energy safety — the availability of electricity — but CO_2 emissions represent only the wintertime emissions. Power generation methods also differ in their capacity over the year, as for example during wintertime wind power is most abundant, hydropower at its low production season, and due to the lack of sun solar power is practically nonexistent. Conversely during summer nuclear power is reduced due to maintenance breaks, solar power is at its peak and demand at its lowest. This can have significant effects on the power production mix, and thus on CO_2 emissions. Furthermore, this error is exaggerated with increasing proportion of wind and solar power production capacity.

4 Parameters

The model contains many parameters that need to match real-world values for the model to have any resemblance to the real Finnish electricity market. These parameters are typically a combination of two features: the maximum or mean power value P_{unit}, and the probability distribution of the normalized capacity factor $P(\hat{C})$. The sections below describe how and from what data source these values were determined. Aside from a few exceptions, the $P(\hat{C})$ value is calculated by first normalizing original capacity measurements C, and an empirical discrete probability density is calculated using bin width of 0.02 (e.g. fifty bins are used for the $\hat{C} \in [0, 1]$ range).

Note that all but a few capacity models are based on data covering winter months from December to February. Any exceptions to this are noted separately. Similarly most models are based on aggregated data and thus are by default aggregated models unless explicitly stated otherwise.

4.1 Demand

The source data is Fingrid's "Electricity consumption in Finland" which is collected every two hours, from which data for winters between 2006 and 2016 was selected [16, variable 128]. The average consumption during winter months is 11 190 MW. The consumption was normalized using the average, and the resulting probability distribution is shown in Figure 4 (left).

The power demand P_{area} for each area was determined by first calculating each area's average yearly consumption in 2016 from Finnish Energy's statistics on municipal electricity usage [17]. Using the ratio between the winter month consumption of 11 190 MW to the average Finnish consumption for the whole year (9 550 MW), the yearly average consumption values were converted to wintertime consumption values.

4.2 Production

4.2.1 Production types

The production capacities for different production types by each area was determined from Energy Authority's registry of Finnish power plants [18] with the exception of solar power for which a list of Finland's largest solar installations at Wikipedia was used [19]. The Energy Authority's registry contains all forms of power production where the power plant or site has 1 MW or more maximum production capacity. To differentiate between different greenhouse gas emissions by production type, power plants were further classified into one of the following categories: biomass, coal, gas, peat, wind, hydro, nuclear, oil, solar, and other.

The resulting list was compared to Jääskeläinen et al's estimations of the *available* production capacity in January 2016. The comparison showed differences between Energy Authority's as detailed in Table 1. For condensing plants and CHP plants the production capacities differ significantly between registry figures and Jääskeläinen et al's estimates. Based on correspondence with one of the paper's authors it was determined that some of

Production type	**Installed Capacity (Energy Authority)** MWh/h	**Estimated Capacity (Jääskeläinen et al.)** MWh/h	**Capacity used** MWh/h
Hydropower	3 025	2 550	3 025
Nuclear power	2 769	2 780	2 769
Condensing power plants	1 649	960	960
CHP district heating	3 922	3 250	3 250
CHP industry	2 951	2 000	2 000
Wind	1 752	60	1 752

Table 1: Production capacities by production method as determined from Energy Authority power plant registry compared to Jääskeläinen et al's estimates of available production capacity in January 2016. This work uses estimates from Jääskeläinen et al's work for condensing power plants, CHP district heating ad CHP industry. The Energy Authority values are used for hydropower and wind power on the basis that Jääskeläinen et al based estimates on the capacity on a single day, whereas in this model the variability of hydro and wind power are modeled using a probability distribution.

the power plants listed in the registry are either not normally available (having a long start-up time, for example), or have been or are planned for decommissioning. For this reason the regional power plant capacities for condensing and CHP plants have been derated to match Jääskeläinen et al's figures. Wind power's low production estimate is based on the wind conditions of that particular day which is already statistically taken into account in the wind power's capacity model (see below). The final production capacities by area are shown in the Table 2.

4.2.2 Wind capacity model

The source data is Fingrid's "Wind power production — real time data" which is reported every three minutes, from which data for winter of 2016–17 was used [16, variable 181]. The average production during winter 2016–17 was 590 MW. The consumption was normalized using the installed maximum capacity (see Table 2), and the resulting probability distribution is shown in Figure 4 (right).

4.2.3 Hydro capacity model

There has been no significant changes on hydropower installed capacity, thus data covering all of the winters from 2010–11 to 2016–11 can be used. The data source is Fingrid's "Hydro power production — real time data", collected every three minutes [16, variable 191]. Since a large portion of hydropower is used in load following mode or as reserve, the direct use of the hydro production measurements would underestimate its availability.

Production category	**Capacity**	**CO_2 emissions**
	MWh/h	t/GWh
Biomass	1 364	240
Coal	1 638	820
Gas	1 128	490
Peat	1 286	914
Wind	1 752	12
Hydro	3 025	24
Nuclear	2 769	12
Oil	552	650
Solar	8	45
Other	235	470

Table 2: Production capacities by the greenhouse gas emissions class categorisation. CO_2 2eq emission values are from IPCC 2014 [20], except for peat and "other" which are based on sources [21, 22].

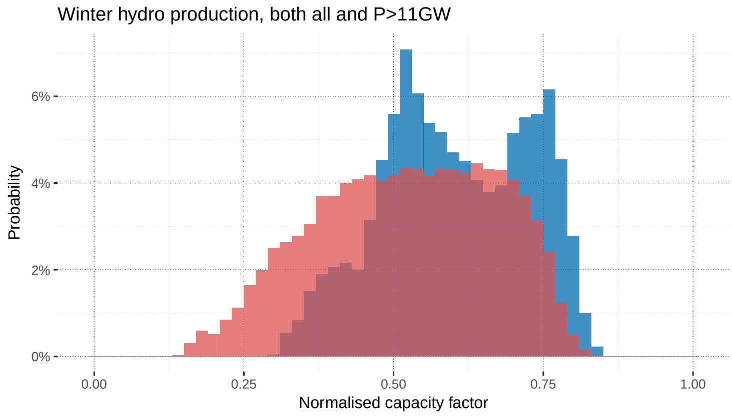


Figure 5: Winter hydro production 2010–16 showing the difference in capacity factors for all production (red) and when only values during total production of 11 GW or more (blue). This shows a two-peak distribution during high peak demand which is caused by the difference between good reservoir capacity and those with low reservoir capacity during winter.

To compensate for the underestimation bias the data was further narrowed to include only periods with a very high electricity demand. The underlying assumption is that a larger portion of hydropower is in use to meet periods of high demand. The high demand was determined as periods of high domestic production from the Fingrid's "Electricity production in Finland — real time data" data set [16, variable 192]. The cutoff limit was arbitrarily set at 11 000 MW of used production capacity.

To illustrate the significance of this difference, see Figure 5. When all winter production values are considered, a relatively flat peak is visible, constrasted to the situation when only >11 GW production values are accounted. The latter high-demand hydrpower generation power distribution shows distinctively two separate peaks which are due to the natural variation of water level in water reservoirs. Using the cutoff value for distribution generation allows the simulation to account for both the low-reservoir and high-reservoir conditions.

4.2.4 Solar capacity model

Finland has very few large-scale solar panel installations. The largest solar power installation current is Helen's Kivikko solar power plant with maximum production capacity of 0.8 MW. Helen publishes Kivikko's real-time production values with one hour accuracy since the plant's start of operations in 2016 [23]. This limits the data set to one winter for the solar capacity model.

The average solar power production is very low during winter (at 5 kWh/h for Kivikko plant) due to the low amount of daytime and low angle of sun during winter months even in Southern Finland. The capacity factor distribution was generated by normalizing the data by Kivikko's nominal maximum production capacity. Since the model is generated from single site data, it is used as an independent model. See Figure 6 for the very bottom-heavy solar capacity distribution.

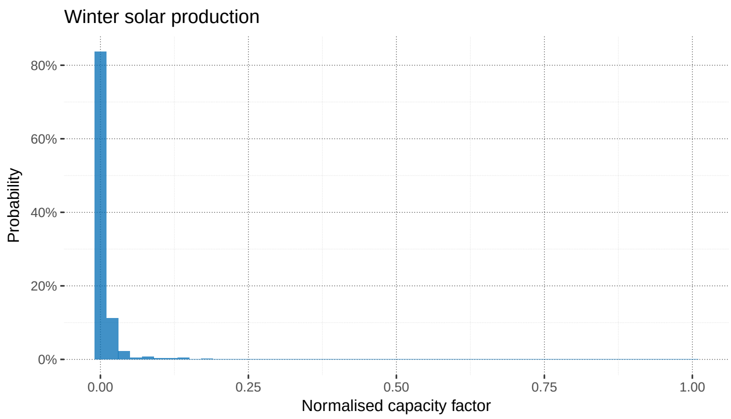


Figure 6: Solar production during winter 2016–17 at the Kivikko solar power plant normalized over the 0.8 MW maximum capacity of the plant.

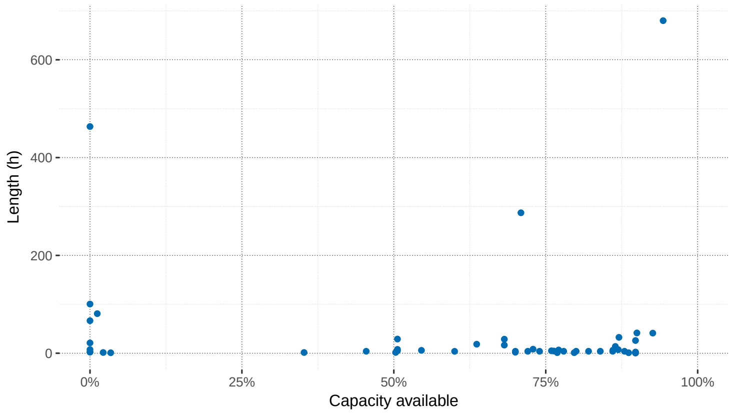


Figure 7: Length of failures and unscheduled maintenance in Finnish nuclear power plants from 2014 to 2016, and the proportion of production capacity available.

4.2.5 Nuclear capacity model

For nuclear power, the Nord Pool Spot “Urgent Market Message” messages were examined for Loviisa 1 & 2, and Olkiluoto 1 & 2 between beginning of 2014 to end of 2016. This information contains both scheduled maintenance and unscheduled failures. Scheduled maintenance events were discarded, since in Finland they occur during summer. Otherwise any failures or unscheduled maintenance affecting production capacity at a nuclear power plant are assumed to be independent. Based on a visual examination (see Figure 7) the capacity model is defined *ad hoc* as having 2% probability of having capacity uniformly in the 0–90% range, and 98% probability of having 100% capacity[7]. The nuclear power plant capacity model is used as an independent model.

4.2.6 Coal, gas, oil, waste and biomass capacity models

The capacity model for other power plants is based on a common set of assumptions. Since all of these plant types share a common physical design of being either condensing power plants or combined heat and power (CHP) plants, the re-use of the same capacity model generation method is warranted. The distribution models were constructed from assuming availability of 97.4% for a single condensing or CHP plant based on information from Fortum [24], and an aggregated model for the whole Finland for a particular fuel type is generated by the statistical resampling method from the single-plant model.

4.2.7 Greenhouse gas emissions

The emissions of CO_2eq for different production methods and fuel types are listed in Table 2. The CO_2eq values are from the IPCC 2014 report [20], with the exception of from peat CO_2 emission values which are based on information from [21], and for the “other” category, which in Finland is mainly from municipal waste (emission information from [22]).

[7] $P(\hat{C} \in [0, 0.9]) = 0.02, P(\hat{C} = 1) = 0.98$

4.3 Transmission

The intra-country transmission capacity was not considered to be relevant to the results of understanding energy policy challenges, and were modeled as 10 GW transmission lines without any capacity variability.

4.4 Imports

The current maximum capacity for transmission lines to Estonia, Norway, Russia, and Sweden were determined from Fingrid's information on planned and actual cross-border transmission capacities into Finland [25]. The imports were determined to be 1 500 MW and 1 200 MW from Sweden (to two separate areas), 1 300 MW from Russia, 100 MW from Norway, and 1 000 MW from Estonia. Although there exists some variability in the cross-country transmission line capacities over time, this was not taken into account in the model.

Since the simulation tries to minimize CO_2 emissions, each import country has a corresponding greenhouse gas emission value which was determined from the country's production mix. The values used were 96 for Sweden, 404 for Russia, 607 for Estonia, and 33 for Norway (in t/GWh).

5 Simulation

5.1 Overview

The simulation is a time-independent, discrete step Monte Carlo simulation[8]. Each independent simulation round consists of first sampling of transmission, demand, and production capacities from their respective capacity models, then performing a flow optimisation to "transfer" electricity along transmission lines from areas with excess production capacity to areas with lack of sufficient production. After transmissions are calculated, model statistics are collected for analysis and a new round is started. Each of these steps are discussed in more detail below[9].

Since the purpose of the simulation is to be illustrative, no special effort has been made on numerical stability — for example, the default random number generator for the runtime environment is used, and to minimize memory use, variances of statistic variables are calculated using the Welford single-pass algorithm as opposed to the exact two-pass algorithm. Thus it is possible that the simulation produces degenerate results on degenerate combinations of the operating environment and model parameters.

As an example on how the simulation proceeds, consider the simple two-area model as shown in Figure 8a. The example model has a maximum demand of 1 300 MW and a maximum production capacity of 2 200 MW with a transmission line of maximum capacity for either direction of 700 MW. The demand is modeled as an aggregate capacity while production and transfer line capacities are independent. At the start of the simulation round no sampling has yet occurred and the $\hat{C}$ values are unset.

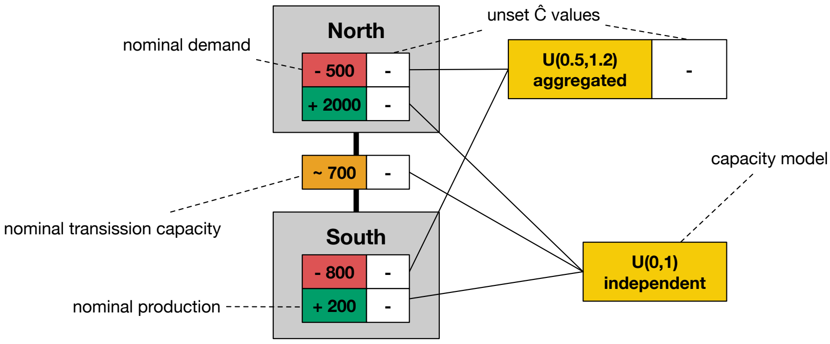
5.2 Capacity sampling

Each transmission, demand, and production unit has its associated capacity model is sampled for capacity factor value $\hat{C}$. If the unit's capacity model is an individual model then each unit is assigned a separate sample from the defined capacity factor distribution $P(\hat{C})$. For aggregated models, the model is sampled only once and all units using the aggregate model get the same value. Each unit has its nominal capacity (either mean or maximum, depending on the model type). Once these values are assigned, they are remain unchanged for the rest of the single simulation round.

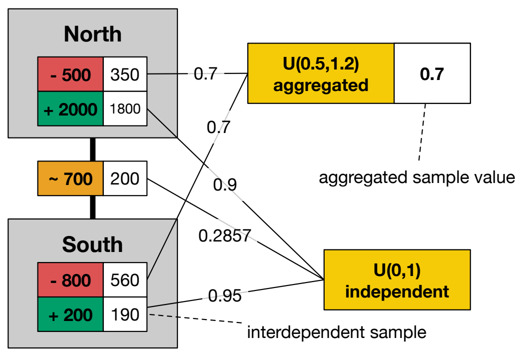
In the example as shown in Figure 8b, the demand in both areas and the transmission line are using an independent capacity model and thus both area's demand and the transmission line capacities are assigned different capacity factors. The demand for both areas is based on an aggregated capacity model, so both have the same capacity factor but since their nominal demand is different they will have different values for the simulation round. At this time the model has actual production capacity of 1 990 MW, demand of 910 MW with a transmission capacity of 200 MW between the two areas.

[8] Monte Carlo simulations are based on random sampling to generate aggregate numerical results, often in situations where no analytical result can be obtained.

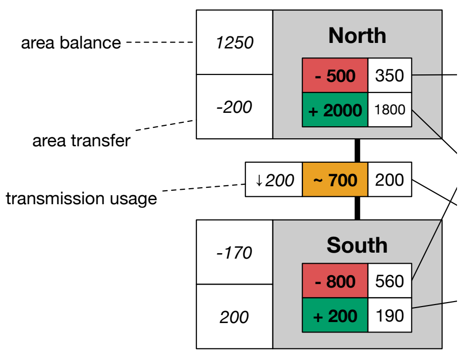
[9] For implementation details please refer to the implementation documentation and the source code at `https://github.com/santtu/energysim`.



(a) Initial state



(b) $\hat{C}$ values sampled and propagated



(c) Transmission flow finished

Figure 8: Example of a model, and the sampling and transmission flow steps of the simulation. Both of the capacity models use an uniform distribution $U(a, b)$.

5.3 Transmission flow

The simulation optimizes the flow of electricity between all areas with two goals: ensure demands are met and greenhouse gas emissions are minized. This optimization occurs iteratively where each iteration adds unused production units with the lowest greenhouse gas emissions (per produced power), then runs the Edmonds-Karp maximum flow algorithm and updates the remaining capacity of production units and transmission lines after each iteration. This process repeats until either all production units have been considered, or all demand has been met.

After transmission flow in the example (see Figure 8c) the transmission line capacity is utilized to its full transmission capacity. At the end of this simulation round the northern area has an excess production capacity of 1 250 MW while the southern area is suffering an outage with 170 MW of unmet demand.

5.4 Statistics

The set of statistics that are collected is primarily used in the user interface and its usage depends on what is considered relevant for the user. As an example, at least all of the following statistics are collected:

- Power balance in each area, transmissions in or out of the area, and the number of rounds where an area had an outage (negative power balance)
- Used and excess production capacity for each unit and area, and the CO_2 emissions from production units
- Used and unused transmission line capacity in both directions separately

These values are collected into summary statistics producing statistical mean and standard deviation of the value as well as a sliding sample history for user interface graphs.

6 Conclusions

The result of this work is a browser-based sandbox simulation of the Finnish electricity market as of approximately 2016–2017. The simulation is accessible for the general public at `energysim.kooma.net`. The electricity production and consumption capacities are based on real-world values sourced from multiple public data sources. As Finland's peak demand occurs during the winter, the model's production and demand capacity probability distributions are based on winter values as well.

This work can be used to model different energy policies. Based on qualitative inspection it appears to produce expected results for several stereotypical energy policies. For example, removing oil and coal, and adding equal amount of average wind production capacity — about 10 GW of increased nominal capacity — does result in occasional blackouts, as would be expected due to the high variability of wind production. Modeling a geopolitical scenario where Russian electricity and gas imports are removed results in frequent blackouts. Finally, adding the Olkiluoto 3 nuclear power plant (about 1 600 MW) results in about 20% reduction of greenhouse gas emissions from the baseline model. As a conclusion, while the simulation is not meant to be a perfect model, it does respond in expected manner to several types of user inputs.

The underlying assumption of this work was that it would be possible to influence people's views on their electricity production preferences and enrich their understanding of the complexities of Finnish energy policy. Unfortunately, testing this assumption was out of the scope of this work, with further work to study the hypothesis and its actual effect. Tis work could include questionnaires for focus groups before and after trying out the simulation to evaluate its effect on people's attitudes towards energy policies.

The simulation is described as a "sandbox" simulation. In game terms, a "sandbox game" does not impose a goal for the player, letting them decide on the gameplay goals by themselves. While several successful games follow the sandbox game model without a specific goal (The Sims and Kerbal Space Program, for example), even they often offer the player an option to choose from a set of challenges. For people not familiar with the game or its capabilities these often act as entryway to the deeper and self-governed aspects of the game. These kinds of predefined goals help to keep the attention of the user on the game by providing them with a feeling of accomplishment along the way. It is possible that adding more goal-oriented gameplay elements to the simulation could work both as an introduction to its mechanics and controls as well as to bring potential future scenarios in Finland to the awareness of the player (such as more demanding CO_2 reduction targets).

Finally, several of the simplifications and abstractions noted in Section 3.3 limit the comprehensiveness of the simulation. The lack of seasonal variation implies that the CO_2 emission values reflect currently *only* the winter-time values. Since electricity demand and especially solar production varies greatly with season this causes an unintuitive response to increase in solar production capacity — it has practically no effect, as the expected capacity factor of solar power during winter is practically zero. Extending the model to address these limitations would make it more applicable as a tool for teaching as the CO_2, electricity demand and production values could be matched with official yearly production, consumption, and emission statistics.

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