Electricity model

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Contents

1 Model conceptualisation

The model presented in this chapter is a transposition of the model created by Paul van Baal and Reinier Verhoog and first created by Paul van Baal for his master thesis (van Baal, 2016). The model has also been further improved to look into the effect of a strategic reserve in a hybrid system dynamics - agent based model version (van Baal and Finger, 2019). In this report, the model, which was a system dynamics model and then a hybrid model, is turned into an agent based model. This report is the ODD presentation of that model (Grimm et al., 2010). All equations and additional details are in the appendices.

1.1 Purpose of the model

The purpose of this model is to simulate the Swiss electricity system. This includes the spot market, international trade with neighbouring countries, and investments. This constitutes what is considered to be the simplest electricity model (SMel). In future iterations of the model, depending on the goals of the research, the model can be extended to consider the presence of demand side management, batteries, prosumers or a strategic reserve.

1.2 Entities, state variables and scales

There are four types of agents within the model: the market operator, the firms (or investors), the supply agents and the demand agents. The market operator is the agent that is in charge of the spot market, making sure everything is going well. The firms are the agents that own the power plants and other assets present in the model. They are in control of the power plants. The demand agents are the agents that buy electricity. This includes the inflexible demand (which is based on a historical scenario), and demand created by hydro-pumping power and international trading.

The firms are characterised by the following attributes: assets owned, electricity supplied, planned assets, retired assets and constructed assets. The supply agents can either be the power plants (assets), they can be long term contracts with France, or they can be the net transfer capacities from the different border countries. Each has a different set of attributes. The assets are characterised by the following attributes: owner, technology type, installed capacity, age, lifespan, capital costs, annual fixed costs, variable costs and utilisation factor. Additionally, depending on the technology type, some power plants have more parameters. For example, the thermal power plants, the nuclear power plants and the waste power plants all have a fuel cost. The thermal power plants also have an emission attribute. The nuclear power plants have attributes related to their maintenance requirements: maintenance month and maintenance time. Waste, hydro and hydro-pumping assets have attributes related to their reservoirs: reservoir level and maximum reservoir level. Hydro-pumping assets have an efficiency attribute related to their pumping efficiency.

The technology types are limited to: solar, wind, hydro power, hydro-pumping power, run of river, thermal, nuclear and waste. The firms can only invest in solar, wind and thermal technologies as it is considered that other technologies are already maxed out in Switzerland or they cannot be used to produce significantly more electricity.

1.3 Process overview and scheduling

The model runs along two different scales, highlighting two parts of the model. The first part is the spot market, running on an hourly basis. It consists of all the actions related to the spot market including all of the inputs, the calculation of the demand, the calculation of the spot price, the distribution of the money and electricity when the equilibrium is found and the update of the NPV for all of the agents (that is later used for investments).

The second part is related to the investments that the firms can perform. This happens monthly. These are actions that are related to the firms. They decide whether to invest in new assets. They also decide whether they should reinvest in their current assets by extending their lifetimes or shuttering them temporarily or definitively. Then there are additional measures that include the end of life actions that occurs when an asset has reached its lifetime. It also includes scenario based events such as the closing of nuclear power plants according to a politically determined timeline.

1.4 Design concepts

Basic principles The model is, in essence, a simple supply and demand model where electricity is demanded and supplied. The main added element is that instead of resolving this supply and demand every week or year as it has been done in past models, it is done on an hourly basis.

Emergence The main outputs of the model relate to the energy mix that is needed to meet the Swiss electricity demand. The investments, their type and amount are also of interest for the purpose of the study and should emerge from the needs to supply electricity.

Adaptation There is no real adaptation programmed in this model beyond agents deciding on whether to discontinue their current assets and whether to invest in current or new ones.

Objectives The objectives for the market operator is that there be a balanced spot market. The objective for the firms is to make as much money as possible. The objective of the supply agents is to supply as much energy as possible. The objective of the demand agents is to have their demand met.

Prediction The firm agents have to use prediction for the investments. They forecast the price of electricity for the next year, two years and five years based on historical data for each technology considered. This is then used in the profitability check and the Net Present Value (NPV) by the firms for their respective assets or future investments.

Sensing The sensing of the actors is limited. Only the firms have sensing. They have a clear and full understanding of the performance of their assets. This includes the costs involved, the electricity generated and sold, and for some technologies, the reservoir related values. For investments, actors only inform their investment potential based on what assets are present in the system and the overall price of electricity. They do not have knowledge of other firm's assets in construction or planned. This can therefore lead to periodical supply surplus.

Stochasticity Most of the model is deterministic. Some outages can occur randomly for each of the plants. Scenarios also provide some stochasticity to the simulation.

Observation The model produces a large amount of data. Not all of it is necessary for testing, understanding and analysis. Some of the data needs to be collected to feed the policy process model. The agents in the policy process based their decision based on what is going on with a set of key performance indicators in the electricity model. Beyond this, the interest for understanding and analysis is mostly focused on the electricity prices, the number of outages (if any), the supply mix, and the trade with foreign countries. Depending on the study being performed, the amount of investment is also of interest along with the type of investment and measures related to the goals of the Energy Strategy 2050.

1.5 Initialisation

The model is initialised with values from 2018 for all of the assets that are present in the model. This includes the 2018 Swiss electricity power plants distribution and costs. The initialisation state is always the same for all simulations. All the values considered are informed on the Swiss electricity sector directly.

1.6 Input data

There are a lot of input data required to simulate the electricity system. The data used to run the model is given below:

- Asset investment (type, sizes and costs)

- The gas prices for thermal power plants (scenario based)
- The emission prices for thermal power plants (scenario based)
- The water inflow in Swiss reservoirs for hydro power plants yearly and hourly (scenario included)
- The waste inflow in Swiss waste management facilities yearly (scenario based)
- The price of nuclear fuel (scenario based)
- The amount of solar radiation hourly (based on the years 2015, 2016 and 2017)
- The amount of wind hourly (based on the years 2015, 2016 and 2017)
- The amount of run of river water (based on the years 2010, 2011, 2012, 2013 and 2014)
- The average hourly electricity price in France, Germany and Italy (based on the years 2015, 2016 and 2017)
- The average border capacity (import and export) with France, Germany and Italy (based on the years 2015, 2016 and 2017)

1.7 Submodels

There is a large number of submodels that are used to simulate the Swiss electricity market. They are all detailed qualitatively within this section. The equations used are present in the appendix for each submodel.

1. The spot market
2. The electricity price forecast
3. The profitability calculation
4. The NPV calculation
5. The end of life actions
6. The international trading
7. The demand aspect of storage in the model

The spot market The spot market is at the centre of the model. Its role is to match supply with demand. Some of the demand is inelastic and always has to be met. Some of it is elastic and will be met depending on the supply price. The spot market includes all of the assets (supply and demand wise) and the international trading. It is cleared on an hourly basis using a merit order curve.

The spot price is calculated using the merit order curve. The cheapest technologies are first selected and then depending on demand, the price moves up to account for other technologies. In the cases where there is not enough supply, the Value of Lost Load (VOLL) is set at 3000 CHF per MWh.

There are two parts for the supply of energy. There is the installed capacity and the available capacity at any point of time. The market is cleared every hour.

The supply that is considered for the spot market is made of: hydropower (including run-of-river, reservoir and pumped storage), nuclear power, CCGT, solar and wind power, long term French nuclear import contracts, interruptible contracts (dischargeable generation option), and thermal power (including green CHP, waste burning power plants, other thermal).

The electricity price forecast The electricity price forecast is used by the firms to gain an understanding of the market and help them assess whether future investments are worth the expenses. This price forecasts consists of estimating a linear relation for the future in the form $y = mx + p$. Therefore finding a slope (m) and a constant (p) for future prices based on prices from the previous four years. This is done using a weighted average of the last three years of prices and is updated throughout the simulation based on the evolution of the price of electricity for each technology.

The profitability calculation Towards the end of life of an asset, within ten years of the end of life, the one year and five profitability of the assets are assessed monthly by the owners. Then several options present themselves. If the one year profitability is negative and the asset has reached its lifetime, then it is decommissioned. If the five year profitability is higher than zero but the one year profitability is negative, then the asset is mothballed. If the one year profitability is positive and the asset has been renovated less than twice, it is renovated. If not, it is decommissioned when it reaches its final age.

The NPV calculation The NPV calculation is used by the actors to assess potential new power plants for their portfolios. The NPV is used to assess the profitability of a future plant. If that profitability is higher than the hurdle rate of the actor, then the actor will consider investing in the plant.

The investment pipeline The firms can invest in three main technologies: solar, wind and thermal power plants. These investments are discrete in capacity. Only one option per technology is provided as an option to the investors. Every month, each firm is provided with the opportunity of investing in one of the three technologies. They test the NPV of each of the plants and the most positive, if there is one, is approved by the firm. Approval at this stage means that a permit is demanded. This is a process that takes a different amount of time depending on the technology. Its rate of success also depend on the technology with the rate of success of solar being affected by land scarcity and the rage of success of wind being affected by land scarcity and social acceptance.

Once the permit has been approved, the firms will once again assess the NPV of the investment on a monthly basis. If the NPV has changed and is now negative, the firm keeps the permit without building the plant. If it becomes positive, then construction is started. The plant then comes online only after the building period has been completed.

The international trading International trading of electricity is introduced in the model. The import and export prices of the electricity are known from historical data for Germany, Italy and France. The supply of this electricity is then limited by the inter-connections to these different countries.

This international trading is supplemented by the long term contracts that Switzerland has with France. Such contracts take a part of the capacity on the interconnections between France and Switzerland, limiting the potential for international trading.

The demand aspect of storage in the model Demand is mostly present in the model through the inelastic demand of Swiss consumers. One can also consider the demand of foreign countries and the demand of storage technologies such as hydro-pumping. All these aspects are taken into account in the spot market to make sure demand is met by supply. In the future, prosumers and their batteries could also be considered as demand agents.

2 Model formalisation

This section outlines the different algorithms that are used within the electricity market model.

Chapter missing key elements like the merit-order curve algorithm.

2.1 Electricity costs calculation per technology

The calculation of the price at which each asset sells its electricity varies depending on the technology considered. The details of the calculations for the marginal costs are presented below:

- For solar power plants:

$$MC_{solar} = VC_{solar} \tag{1}$$

  where MC are the marginal costs and VC are the variable costs.

- For wind power plants:

$$MC_{wind} = VC_{wind} \tag{2}$$

- For hydro and hydro-pumping power plants:

$$MC_{hydro} = OC + VC_{hydro} \tag{3}$$

  where OC are the opportunity costs.

  The opportunity costs are calculated using the price reference and depend on the amount of water that is left in the reservoir of the hydro power plant. The price reference is calculated based on the weighted average of the previous three year electricity price on the spot market in the previous years.

$$P_{ref} = 2 \cdot \frac{3 \cdot P_{t-1} + 2 \cdot P_{t-2} + P_{t-3}}{6} \tag{4}$$

where P is the average price of electricity on a given year and t is the year within which the simulation is.

If the installed capacity is larger than the water left in the reservoir then, the opportunity costs are:

$$OC = (P_{ref} - VC_{hydro}) \cdot \left(1 - \frac{RL}{2 \cdot RC_{max}}\right) \tag{5}$$

If the opposite is true, then:

$$OC = (P_{ref} - VC_{hydro}) \cdot \left(1 - \frac{RL - IC}{RC_{max}}\right) \tag{6}$$

where RL is the reservoir level, IC is the installed capacity and RC is the reservoir capacity

- For run of river plants:

$$MC_{ror} = VC_{ror} \tag{7}$$

- For waste management power plants:

$$MC_{waste} = OC_{waste} \tag{8}$$

Here the costs are calculated using the opportunity costs again. These can be found using the same equations as for hydro power plants.

- For thermal power plants:

$$MC_{thermal} = FC + VC_{thermal} \tag{9}$$

where FC are the fuel costs. The fuel costs include both the gas price and the carbon price. This considers a price for carbon that varies over time and emissions of 0.342834 tons/MWh (NREL, 2018).

Below is the carbon prices scenario:

2017	9
2020	15
2025	22
2030	33
2035	42
2050	73

- For nuclear power plants:

$$MC_{nuclear} = FC + VC_{nuclear} \tag{10}$$

2.2 Supply amount per technology

The amount of electricity supplied per technology is given using the following equations:

- For solar power plants:

$$S_{solar} = C \cdot Solar_{conditions} * UF \tag{11}$$

  where S is the supply, $Solar_{conditions}$ is an input file defining how much solar electricity was produced for every hour of the year historically, UF is the potential utilisation factor. The potential utilisation factor is calculated based on a curve that helps assess the best locations for solar and the maximum theoretical amount of roof top solar in Switzerland. The curve is given below:

0	0.147
0.0367	0.1358
0.9306	0.114155
1	0.100114

- For wind power plants:

$$S_{wind} = C \cdot Wind_{conditions} * UF \tag{12}$$

  where $Wind_{conditions}$ is an input file defining how much solar electricity was produced for every hour of the year historically, UF is the potential utilisation factor. The potential utilisation factor is calculated based on a curve that helps assess the best locations for wind and the maximum theoretical amount of wind power in Switzerland. The curve is given below:

0	0.3196
0.181	0.2497
0.195	0.2457
0.267	0.2301
1	0.1608

- For hydro, hydro-pumping and waste power plants:

  The supply of electricity is dependent on the level of the reservoir. If the reservoir level is below the capacity of the power plant, then the reservoir level is the amount supplied, otherwise, the capacity of the power plant is the electricity supplied.

- For run of river power plants:

$$S_{ror} = flow_{ror} \cdot growth_{ror} \cdot C_{ror} \tag{13}$$

  where C is the installed capacity and the flow is dependent on weather input data.

  The run of river growth factor represents the growth of such production over the year. It is based on a scenario provided in Table 1 and can be calculated using the following equation:

$$growth_{ror} = C_{ror,scenario}/C_{ror,installed} \tag{14}$$

  This considers the entire run of river production within Switzerland and not just one plant.

2015	16400
2020	16700
2025	16933
2035	17533
2050	18333

Table 1: Expected total production for all run of river power plants in GWh.

- For thermal power plants:

$$S_{thermal} = C \tag{15}$$

- For nuclear power plants:

$$S_{nuclear} = C \tag{16}$$

  Note that nuclear power plants are not online throughout the year. They have a yearly planned maintenance, usually planned in the summer when the plant is offline. This is a done over a period of thirty days. Each starting month is specified as an input per asset.

2.3 Investment approach

The electricity price forecast is used for the investments. This price forecasts consists of estimating a linear relation for the future in the form $y = mx + p$.

The slope m is calculated using the following equation:

$$U = \frac{P_{t-0} + P_{t-1} + P_{t-2} + P_{t-3}}{4} \tag{17}$$

$$m = \frac{-3 \cdot (P_{t-3} - U) - (P_{t-2} - U) + (P_{t-1} - U) + 3 \cdot (P_{t-0} - U)}{2 \cdot 2015} \tag{18}$$

The constant p is given by:

$$p = U - t * m \tag{19}$$

where t is the time at which the simulation is at.

The profitability of an asset is calculated using the following equation:

$$P = \left(\sum^{t} \frac{((Y + t) \cdot m + p) - VC}{(1 + r)^{t+1}} \right) \cdot 8760 \cdot \epsilon \cdot C \tag{20}$$

where P are the profits, Y is the initial year, t the year for which profitability is considered after the initial year, VC the variable costs, r the discount rate, ϵ the utilisation rate and C the capacity of the asset considered.

The losses are calculated using:

$$L = \left(\sum^{t} \left[1 + \frac{1}{(1+r)^{t+1}} \right] \right) \cdot FC \cdot C \tag{21}$$

where L are the losses, C is the capacity of the plant and FC are the annual fixed costs of the plant.

The profitability is then calculated as the difference between profits and losses.

For investments, the actors use the NPV and the profitability index of potential new power plants.

The following equations are used to estimate the NPV.

$$NPV = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n} = \sum_{n=0}^{N} \frac{(R - MC) * \epsilon - OC}{(1 + WACC)^n} \tag{22}$$

where R are the revenues per year, ϵ is the utilisation factor, MC are the marginal costs, OC are the fixed operating costs. WACC is given as the sum of the risk rate and the discount rate.

3 Code documentation

This is the detailed documentation, file by file of the Swiss electricity market model.

3.1 run_elec.py

This is the file that is used to the electricity model. It has for input the duration of the runs in years. It then initialise the electricity model.

The script is using a loop where each iteration is one year. This is the `step()` function of the `model_elec.py` file.

For checks, some of the results can be plotted every five years.

Once the simulation has ended, the data is extracted from the `datacollector` and save as a `.csv` file.

3.2 model_elec.py

This script is composed of two main parts: the `get_supply` functions at the beginning and the `class Electricity(Model)`. The functions are there for the datacollector. They are used to collect the data that needs to be saved from the model. They are outside of the class and only called by the datacollector following the architecture provided by mesa. Each of the functions returns what needs to be recorded and only that.

The `class Electricity(Model)` begins with the initialisation of all the parameters that are needed for the simulation of the electricity model. This is detailed within the python file itself and is not detailed here.

The functions:

- `policy_implementation()`

  This function is used exclusively for the hybrid model. It implements whichever policy has been chosen by the policy makers through a modification of a number of pre-defined parameters. This function is not used when the electricity model is run alone.

- `step()`

  This function is used to simulate one year of the policy process. It includes the implementation of the policies, the iteration over 8760 hours and the calculation of the KPIs needed for the hybrid model at the end. The function returns the KPIs.

- `step_hourly()`

  This is the main function of the electricity model. It does whatever needs to be run over an hour. This includes the merit-order curve construction and the selection of the point of supply and demand, it includes the investment of the actors and it includes all of the recording of the data points within the model.

  For the merit order curve: first the supply list is built, this is followed by the construction of the demand list. The point at which these cross is then calculated. Once it has been found, the electricity supplied is allocated to the different assets along with the amount of electricity. This is also true for the demand for the asset that have a certain demand.

The first part of the merit curve is to construct the supply list. This list is composed of all of the assets and the supply they can provide and at what price. This calculate for each asset depending on the technology considered. The list is then sorted by prices which the assets that offer supply at the lower price at the front of the list and the most expensive ones at the end. This also includes a probability that certain assets will go offline due to unexpected maintenance.

The same is then done for the demand list. But the list is ordered in the opposite sense with the highest demand prices at the front of the list and the lowest at the back. The demand list is only made of the inelastic demand, the demand from bordering countries and the demand from hydro power plants.

Then, there is a need to find at which point the two list cross. That is when the demand meets the supply at the same price. This is done using an algorithm that runs through each of the lists. Every time the supply has been allocated to demand, supply of a new asset is added and vice versa. This algorithm also takes into account that capacity allocated from France through the NTC or LTC needs to add up to the total of the border capacity and not go over that limit. This results is dynamically adjusting the supply and demand lists as supply and demand are allocated.

In some instances, when there is not enough supply to meet the inelastic demand, it is possible for there to be a blackout.

Once the point where supply meets demand has been found, the algorithm stop and the electricity price for that specific hour has been defined. The supply is allocated to the different assets along with the demand. This allows for the calculation of the utilisation factor of the different technologies later on. The revenue per assets are also attributed.

After the merit-order curve come the so-called end of step actions. This lumps all of the other actions that can be performed in a step. It includes mandatory actions along with opportunity actions (such as investments).

These include:

- Nuclear asset maintenance

  - Asset ageing: simple iteration of one year for the age parameter for all assets
  - Investment algorithms: investors must decide whether they want to invest in new assets or not
  - End of life actions for assets: potential decommissioning, mothballing or re-investment in assets.
  - Planned assets actions: assets that are already planned need to be advanced in their steps, either constructed or put on hold.

- `hydro_demand_supply_check`

  This is a function that is used to reset the hydro supply or demand if it is already supplying or demanding. This is done to avoid having a hydro pumping plant both providing and supplying. This only affect hydro pumping assets.

- `end_of_life`

  This function is used to perform the so-called end of life actions. This is divided in two parts. For the long term contracts, if they come to the end of their life they are decommissioned and put off line.

  For the nuclear, wind, solar and CCGT assets, if these assets are within ten years of their end of life, it consists of checking if the asset is profitable. This calls the next function with different actions depending on the profitability of the asset. If the asset is already mothballed, then a different set of profitability checks are performed.

- `end_of_life_profitability`

  This function is used to assess the profitability of plants at their of life and perform the necessary actions based on the results of this profitability.

  First one year and five year profitability are calculated. Based on the results of these calculations, actions are taken.

  - If the one year profitability is negative and the age of the asset is past its maximum lifetime, the asset is decommissioned.
  - If the one year profitability is negative but the five year is positive and the asset is not past its lifetime, the asset is mothballed.

- If the one year profitability is positive and the asset is not past its lifetime:
    * If the the asset has not yet been renovated, it is renovated and its life is extended by five years.
    * If the asset has already been renovated too much, it is decommissioned.

- `asset_decommissioning`

  This function remove the asset that has been decommissioned from the asset schedule. Additionally, if the asset is a solar or a wind asset, then the utilisation factor potential for these assets is recalculated.

- `asset_mothball`

  This function mothballs an asset. It puts it offline and extends its overall lifetime by one year.

- `asset_demothball`

  This function puts back online assets that have been mothballed.

- `saving_supply`

  This is the function that record the supply for each technology. This is done hourly, every time the merit-order curve has been completed.

- `saving_demand`

  This is the function that record the demand for each technology (hydro pumping and NTC. This is done hourly, every time the merit-order curve has been completed.

- `planned_assets_invest`

  This is the function that is used to deal with the assets that are planned. These are stored in a list when the investors have decided to submit a permit. Each planned asset goes through a certain number of steps.

  Each planned asset has to go through a planning time, then, if approved, it is placed in a waiting list. If the asset if planned to be profitable, it is constructed by the investor. If not, it stays there until the end of the plan lifetime. At the end of the life of the plan, the asset is removed from the list of planned assets. The actions are provided as follows:

- If asset is in the approval process.

  If the asset has gone through the process time, check if the plan is approved. If approved, move to the waiting list for construction, if not remove asset from the planned asset list.

- If the asset has been approved but is not in construction.

  If the asset has been too long planned and not constructed, it is removed from the list. If this is not the case, and its profitability index is higher than the hurdle rate, then the asset is placed in construction.

- If the asset is in construction.

  If the asset has completed its construction time, it is added to the list of online assets for electricity generation.

Not that with this loop, one assumes that the process for all technology types (solar, wind and CCGT) is the same.

- `elec_UF_elec_prices_updates`

  This function is used to update the utilisation factors for solar, wind, CCGT and nuclear technology types. It is also used to update the historical price of these technologies. These prices are the ones used to extrapolate future prices for the NPV and profitability calculations. This is done yearly.

- `pp_investment_recording`

  This function is used to record the amount of investments in the different technologies. This is used to inform the policy makers within the hybrid model.

- `pp_supply_recording`

  This function is used to record all of the supply over a year for the different technologies. These are stored within a dictionary.

- `parameter_update_yearly`

  This function performs all the parameter updates that are needed yearly. This includes:

- Update the technology parameters depending on pre-set input scenarios (emissions costs, variable costs, ...).
- Update the utilisation factor and electricity prices for each technology type (see `elec_UF_elec_prices_updates`), the general electricity prices, the cumulative electricity prices, the run of river growth potential and the demand growth.
- Reset revenue, and supply for all assets.
- Calculation of the utilisation factor per asset.

- `parameter_update_hourly`

  This function performs all the parameter updates that are needed hourly. This includes:

  - Reset the hourly supply recording, the hourly demand recording, the demand met parameter and the blackout boolean.
  - Update the hydropower and waste reservoirs.
  - Update the import and export values for the NTC assets.
  - Update the ages of the assets and the planned assets.
  - Update of the wind and solar conditions.
  - Introduction of random outages.
  - Calculation of the price preference for the opportunity costs calculation.

- `calculation_solar_UF_potential`

  This function is used to determine the utilisation factor potential for solar installations. This is based on the maximum theoretical solar production in Switzerland and the total capacity already installed.

- `calculation_wind_UF_potential`

  This function is used to determine the utilisation factor potential for wind installations. This is based on the maximum theoretical wind production in Switzerland and the total capacity already installed.

- `pp_KPI_calculation`

  This function is only used as part of the hybrid model. It calculates the KPIs that are needed for the policy actors within the policy emergence model. Each KPI is calculated separately. It consists of:

  - Renewable energy production (S1)

    The calculation is made between the total supply and the total renewable supply (solar, wind, run of river, hydro and hydro pumping). Note that the total supply does not include the NTC and LTC supply. It is then normalised where 0 is no renewable production and 1 is only renewable production.

  - Electricity prices (S2)

    The electricity price average is calculated using the last year average price. It is then normalised with the assumption that the maximum average yearly electricity price cannot go above 150 CHF. If this value turns out to be too low, a warning message will de displayed to tune the model accordingly.

  - Renewable energy investment level (S3)

    The renewable energy investment level is calculating by looking at all investments (wind, solar and CCGT) and comparing it to the amount of renewable investment (wind and solar). A value of 0 means that there is no renewable investment and 1 that there is only renewable investments. Note that the investment only over the previous year are considered and not since the last time a policy was considered.

  - Domestic emissions level (S4)

    The emissions are calculated using the CCGT-provided supply. They are normalised using an estimated highest amount. In this case, a value of 0 means that the domestic emissions are high and a value of 1 means that they are low.

  - Imported emissions level (S5)

    The imported emissions are calculated using an estimation, based on scenarios, of the electricity mix of bordering countries, and the importations of Switzerland. The share of coal and CCGT is considered along with their respective emissions. This is normalised with an arbitrarily selected maximum level. A value of 0 means high imported emissions and a value of 1 means low emissions.

  – Economy (PC1)

    The economy indicator is calculated through a weighted function that considers the electricity prices and the amount of investments only.

  – Environment (PC2)

    The environment indicator is also calculated using a weighted function. It considers the amount of renewable energy, the amount of investments, the amount of domestic emissions and the amount of imported emissions.

- `get_supply`

  The `get_supply` functions are numerous and not within the main class. They are used for the datacollector. They are not used anywhere else. Each function is used to collect a specific data point of the model. This is done hourly, when the datacollector function is called.

3.3 asset.py

This file is used to redefine the asset class. It copies and modifies the `Asset` class from mesa (former `Agent` class) and introduces the `AssetWCost` class for as a subclass of it. The new class is introduced for assets for which costs are needed and are present in the calculations. This consists of all assets except for the `LTContract` and `NTCAsset`.

There are no functions that are used at this level of the `Asset`.

3.4 model_elec_agents.py

3.5 model_elec_assets.py

This script included each of the different technology types. Each technology type is its own class and has a number of functions that are used to determine the costs at which electricity is sold for that technology and the amount that can be supplied. Additional function are also sometimes present.

- `calculation_opportunity_cost`

- `PlannedAsset()`
- `SolarAsset(AsssetWCost)`
  - `calculation_cost`
  - `calculation_supply`
- `WindAsset(AsssetWCost)`
  - `calculation_cost`
  - `calculation_supply`
- `HydroAsset(AsssetWCost)`
  - `calculation_cost`
  - `calculation_supply`
  - `reservoir_step_update`
- `HydroPumpingAsset(AsssetWCost)`
  - `calculation_cost`
  - `calculation_supply`
  - `calculation_cost_demand`
  - `reservoir_step_update`
- `RunOfRiverAsset(AsssetWCost)`
  - `calculation_cost`
  - `calculation_supply`
- `WasteAsset(AsssetWCost)`
  - `calculation_cost`
  - `calculation_supply`
  - `reservoir_step_update`
- `CCGTAsset(AsssetWCost)`
  - `calculation_cost`

  - calculation_supply

- NuclearAsset(AsssetWCost)
  - calculation_cost
  - calculation_supply
- LTContract(Asset)
  - calculation_cost
  - calculation_supply
- NTCAsset(Asset)
  - calculation_cost
  - calculation_supply
  - calculation_demand

3.6 model_elec_agents_init.py

3.7 model_elec_assets_init.py

4 Model inputs

This section outlines the inputs that are used to initialise the electricity market model.

4.1 Asset investments

Firms can invest in thermal, solar and wind technologies. The investments are discrete choices that are detailed below. Note that the costs change over time non-linearly, not all points are outlined below.

Parameters	Thermal	Solar	Wind
Size [MW]	250	100	100
Permit time [months]	36	0.5	6
Construction time [months]	36	12	36
Plant lifetime [years]	55	30	25
Rejection rate [%]	20	20	60
Annual fixed costs [CHF/kWh-year][2018]	10.4	49.3	8.8
Annual fixed costs [CHF/kWh-year][2035]	10.4	38.8	4.7
Variable costs	2.7	0	0
Utilisation factor [%]	0	20	20
Investment costs [CHF/kWh] [2018]	1 051.5	940.5	1 396.9
Investment costs [CHF/kWh] [2035]	983.8	553.2	672.1

4.2 Gas and emission prices

The carbon prices are set based on a scenario provided by Demiray et al. (2018). The gas prices are taken from NREL (2018). They are given in the table below:

Year	Gas prices	Emission prices [CHF/ton$_{CO_2}$]
2017	47.333	9
2020	54.906	15
2025	58.693	22
2030	62.479	33
2035	70.053	42
2050	92.773	73

4.3 Water inflow

The yearly water inflow is provided as a scenario from VSE (2012):

Year	Inflow
2015	18 733 000
2020	18 767 000
2025	18 767 000
2035	18 83 3000
2050	18 933 000

There is also a hourly profile in percentage of water per year that is obtained from four reference years. These are the years 2010 to 2014. These are obtained from Demiray et al. (2018). They are used in a loop throughout the simulation to calculate the hourly inflow in litter into the reservoirs.

4.4 Waste inflow

The average waste inflow in Switzerland is of 233 MW per hour over the entire year. Within the model, it is assumed that this remains constant throughout the year. This is based on electricity statistics for 2016 (2041 GWh per year).

4.5 Nuclear fuel price

The price of nuclear fuel is set at 7 $/MWh (NREL, 2018).

4.6 Solar radiation and wind capacity

The average Swiss solar radiation is obtained from the years 2015 to 2017. These are then used in a loop for the rest of the simulation. This is similar for the wind and for the same year (SFOE, 2018).

Solar theoretical maximum is 19 702 MW, wind theoretical maximum is 2 282 MW. The lookups used for the code are provided below. Note that currently in the code these are implemented as step function and not as linear continuous functions.

Lookup solar	
0	0.147
0.0367	0.1358
0.9306	0.114155
1	0.100114

Lookup wind	
0	0.3196
0.181	0.2497
0.195	0.2457
0.267	0.2301
1	0.1608

4.7 Run of river

For the run of river capacity, an hourly profile is used as input. It is based on data from the years 2010 to 2014 that is looped through for the simulation. The source for this data is Demiray et al. (2018).

This needs to be checked (the data is not obtained where the reference indicates) - what is used in the code is placed in the table.

Year	Inflow [kWh]
2015	16 400 000
2020	16 700 000
2025	16 933 000
2035	17 533 000
2050	18 333 000

4.8 Foreign capacity

The foreign aspect of the model is also dealt with input data. For the prices, they are obtained based on average prices in France, Germany and Italy between 2015 and 2017. Similarly for the average border capacity both for imports and exports, this is used hourly from the input data of the years 2015 to 2017. This data is obtained from the ENTSO-E transparency platform (ENTSO-E, 2018).

References

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A Dear Diary

This section outlines some passing thoughts as the model is being developped.

A.1 22/10/2019

In the current iteration of the model, all actors of the same affiliation practically have the same beliefs. Because there is no communication and perfect knowledge and information transmission, this means that the majority affiliation always decides on what policy instruments should be implemented based on their interests. If summarise, this means that one policy maker of the majority affiliation decides what policy should be implemented. This can be seen as a problem because it effectively means that the entire policy process part of the model is pretty much useless.

However, if one were to think that we are only studying the impact of the electorate on policy change, then this is not so much of a problem. As the preferred states of the agents evolve over time, the policy selected might change. If it is limited to that then it might be fine.

One way to make this more interesting would be to change the consensus criterion to one where 2/3rd of the actors need to prefer a policy instrument for it to be implemented. This, along with a different way to counting which instruments are preferred by 2/3rd of the actors would be needed. In such a scenario, the opposition would have a say on what policy instrument is implemented. This might further better represent Switzerland which tends to be a compromise country.

A.2 23/10/2019

One of the reasons why the actors always select policy instrument 0 is that all policy instruments just have very little impact on the model. Therefore, PI0 is always the one that is selected because it is always slightly better.

There could also just be a lack of verification of the run_batch elements. This needs to be further checked. Because even when the actors had different beliefs (the ones from the predation model of all models), then they also chose PI0.

PI1 has been selected once on time step 5 for scenario 2 growth of 0%.

What about the fact that maybe the testing period of these policies is too limited, giving bad advice to the actors and therefore leading them to make bad decisions. This could be fixed by changing the amount of year checked every time. This is also very computationally inefficient.

Test the model with 9 years of check for each policy instead of the current three.

A.3 24/10/2019

Today I am running the model for an evaluation interval of ten years on the desktop to check whether the results are affected.

On a simulation with evaluation interval of 3, for scenario 2 growth 0%, step 1 has selected PI9. Overall the rest of the selection seems to remain on PI0 for the majority of the time.

On a simulation with evaluation interval of 10, for scenario 1 growth 1%, step 1 has selected PI4. Overall the rest of the selection seems to remain on PI0 for the majority of the time.

From an early look at the simulations, the evaluation interval change does not seem to affect the policy outcomes within the model.

PI4 selected again once for another simulation.

A.4 25/10/2019

Performing verification on the policy instrument selection, it appears that the preference for all of the instruments is the same (0.091) for all actors. This means that there is a problem in the selection of the policy instruments. Maybe check this with the predation model and then see how that changes in the electricity model.

Looking at the predation model, this does not appear to be a systematic issue with the policy emergence model. It seems to be a problem for the electricity model only.

A mistake was found in the core of the model where the policy are evaluated. There was an indices problems when the results were compared to the initial KPIs meaning the agents were assessing the wrong policies (basically). It has been fixed and changed in all models (that now need to be rerun as well).

One thing that still needs to be checked is, though all agents get the same information, they should have different policy instrument preferences based on their secondary goals. This does not seem to be the case for now in the electricity model. This needs to be checked.

Looking at the predation model, it seems that the root of all problems is in the selection of the policy instruments based on preferences. The preferences do not add up to 1 (which they should).