Towards a simulation model of the Bavarian electrical energy system

Marco Pruckner, Peter Bazan, Reinhard German

Computer Science 7 (Computer Networks and Communication Systems)
Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU)
Martensstr. 3
D-91058 Erlangen, GERMANY
{marco.pruckner, peter.bazan, german}@cs.fau.de

Abstract: This paper describes a first version of a simulation model of the electrical energy system for the German federal state Bavaria in order to analyse its energy balance during the nuclear phaseout and the increase of renewable energy sources as well as energy storage capacities. According to current plans, in ten years 50 percent of the Bavarian electric power consumption should be covered by renewable energy sources like water, wind, photovoltaics, biomass (including biogas) and geothermal energy. In addition, the number of gas power plants and pumped-storage hydroelectric plants should be enlarged while the demand for energy should be kept on a constant level. We present a hybrid simulation model using the system dynamics paradigm for modeling energy flows and using discrete-event simulation for the change of conditions (e.g., load and generation) as well as control decisions. The generation system is guided by the electric power demand and is divided into the non-fluctuating conventional power plants like nuclear, gas, oil, coal, biomass and geothermal energy power plants and volatile power plants like wind and photovoltaic parks. We present first results for two relevant scenarios. According to its modular architecture, the simulation model can be extended in order to include more relevant system aspects.

1 Introduction

The decision of the German government phasing out nuclear energy provides a significant challenge for the energy system of the German federal state Bavaria since at present nearly 60 percent of the Bavarian power generation is provided by nuclear power plants. Therefore the planned shift of the energy system is connected with opportunities and risks. In May 2011 the Bavarian government passed the energy concept “Energie innovativ” [Bay11] explaining the strategy for the conversion of the power supply in the next ten years. As one element, the expansion of renewable energy sources should take place significantly faster than planned earlier: 50 percent of the Bavarian electric power demand should be covered by renewable energy sources. Moreover, the loss of nuclear power should be compensated by building more gas power plants with a total generation power of up to 4 GW. Additionally, existing storage capacities of pumped-storage hydroelectric plants of currently about 3.35 GWh should be extended up to 13 GWh, approximately.

In order to support the various stakeholders during that conversion, a research project has been launched to develop a combined simulation and optimization model[1] in order to perform an energy system analysis. The goal of this model is to represent the most relevant parts of this complex system in order to come closer to its understanding, to provide a tool for the investigation of various scenarios, to find risks and miscalculations and finally to support the conversion into a sustainable future system. The simulation model must capture the fluctuations of renewable energy sources, the priority over fossil power plants (according to law in Germany) and the effects of the merit order (leading to a priority between fossil power plants). Furthermore, the model must represent typical load demand variations and it needs to capture the interaction with energy storages.

In this paper we present a first version of a hybrid simulation model to investigate the energy system of a state like Bavaria. Through the configuration of the model we have the possibility to apply our model to another region on the scale of a federal state or even whole Germany. For this purpose, basic components of energy systems are provided. The basic components describe centralized conventional power plants with a certain capacity and fuel, decentralized solar modules together with a stochastic model of fluctuating solar insolation and decentralized wind power stations together with a stochastic model of fluctuating wind speeds. One more basic component represents a stochastic model of the aggregate electricity demand of Bavarian industry companies and households. Moreover, we consider pumped-storage hydroelectric stations, which already play an important role in the Bavarian energy system as energy storages. The basic components are then combined in order to form the energy system of Bavaria.

With our first modeling approach we are able to validate the decision of the Bavarian state government to enlarge the percentage of renewable energy sources on the energy production from 23 percent in 2009 to 50 percent in 2022. As a first scenario we investigate the enlargement of renewable energy sources, gas power plants and pumped-storage hydroelectric stations as it was published in [Bay11]. In a second scenario we analyze the effect without the extension of pumped-storage hydroelectric plants on the annual energy balance.

A main contribution of the paper is a first modeling approach for components of the energy system on the scale of a state of Germany. A second contribution is a simulation model for interactions between fluctuating generation, volatile demand and energy storages on this scale.

The rest of this paper is organized as follows. In Chapter 2 related work is discussed, Chapter 3 shows the simulation model and explains the basic components, Chapter 4 defines different scenarios with respect to different extension plans of pumped-storage

[1] The research project is funded by a consortium of the Bavarian government and various companies from the energy sector and is coordinated by Bayern Innovativ (www.bayern-innovativ.de) and its Cluster Energy Technology. The optimization model is developed by the Chair for Economics, Discrete Optimization, Mathematics (EDOM) at FAU.

hydroelectric plants. Chapter 5 presents the results of eletric energy im- and exports of Bavaria for the described scenarios. Chapter 6 concludes the paper.

2 Related Work

The detailed simulation of the fluctuating energy production and the interaction with storages is a current subject of research (see [BM10]). However, at present it is only available on a smaller scale and not for a region on the scale of a state of Germany. Established forecasts for the development of the German energy system, such as [SLL10], generate scenarios for the future energy system under socio-economic conditions. A consideration of the emerging dynamic growth of renewable energies is usually not taken into account. Furthermore no methodological background for the calculation of these forecasts is given. In [NPS10] a coupled model consisting of an optimization model REMix for modeling the European – North African energy network and a simulation model SimEE for modeling the dynamics of energy producers, consumers and storages in a minute-by-minute resolution is given. The World Energy Model [IEA11] is a complex simulation model for worldwide energy forecasts, whereas [BBF11] considers a similar model to determine the economic and environmental consequences of the nuclear phaseout. However, the modeling of all relevant mechanism for balancing the differences of fluctuating energy production, volatile demand and different energy storages is not examined sufficiently.

A hybrid simulation model for photovoltaic generators and storage units is presented in [MZC09]. They apply the simulation software AnyLogic and use both SD and agent-based modeling. Their solar insolation model is the basis for our model. [DB09] describes an object-oriented model of a microgrid with a stochastic wind model and a centralized control which is implemented in AnyLogic. The stochastic wind model is refined in [KLV11] and would be an interesting extension for a new version of our model. In [BG12] a hybrid simulation model is presented for the analysis of a grid of domestic homes equipped with different energy options such as solar panels, micro combined heat and power systems, batteries as well as energy carriers based on hydrogen. The simulation model presented in this paper follows a similar line but has been adapted in order to represent the dynamics of the energy system of a whole state.

3 Simulation Model

In this chapter we describe the simulation model. First we give a general overview of the overall simulation model, afterwards we specify the basic components like conventional power plants, fluctuating producers, demand profiles and storage technologies.

The model is a hybrid simulation model. Discrete event models represent fluctuations like change of wind speeds and of solar insolations. For example, the weather in the solar insolation model is chosen by a discrete event. Also alternating demand is modeled by discrete-event models. Continuous processes like energy flows are modeled by linear differential equations and are represented by system dynamics (SD) models. We apply the simulation software AnyLogic [XJ12] which allows to combine discrete-event models and system dynamics models in one framework. Components are active objects with internal SD and discrete-event parts and can be dynamically connected at run-time.

3.1 Overall Model

As shown in Figure 1, we consider a region on the scale of a state of Germany, e.g. Bavaria. On the left hand side the different energy producers are separated in non-fluctuating producers like nuclear energy, coal, gas, oil, geothermal energy, hydraulic energy, biomass, waste and fluctuating producers like wind energy and photovoltaics (it should be noted that some producers of the first group also show significant fluctuations e.g., hydraulic energy, but those fluctuations are currently not represented in the model). The right hand side represents the demand side with a combined load profile for households and different branches of industry like heavy industry and small companies. At the top we see an external electricity net component which allows to import and export energy, if too little energy and too much energy inside Bavaria is produced, respectively. At the bottom storage opportunities like pumped-storage hydroelectric stations are arranged.

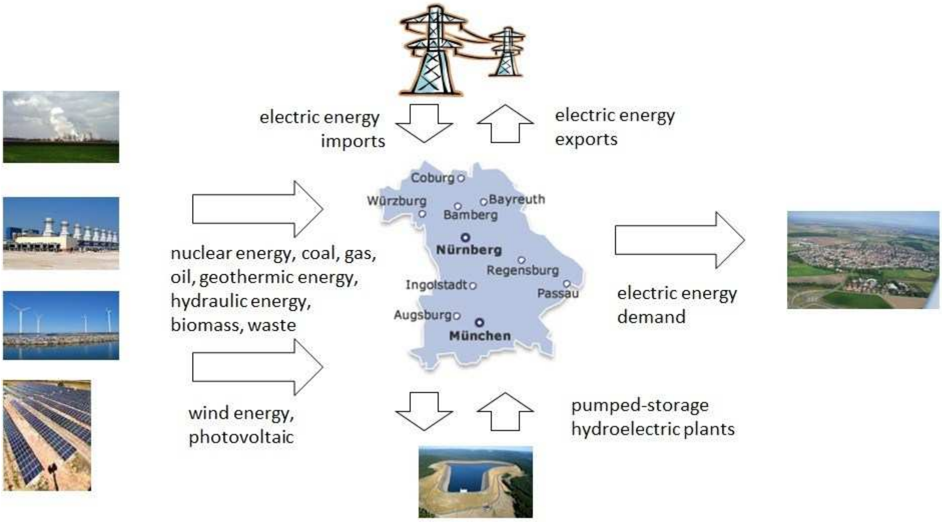

Figure 1: Basic concept of the simulation model

Figure 2 illustrates the implementation of the model in AnyLogic. Energy flows are represented by a system dynamics model. The grid variable should be zero for an equalized balance of energy in every simulation step (differences are devoted to numerical errors). The rectangles represent the accumulated supplied and demanded energy, respectively. Energy flows in GW are represented by arrows from and to the grid.

On the non-fluctuating producer side we distinguish between constant producers like nuclear power plants, hydro-electric power stations, biomass power plants and geothermal energy stations. The operation of coal, waste and gas power plants is done in a load-driven manner. The order of operation is geared to the merit order, i.e., coal before gas and gas before oil. If the current demand can not be covered by the energy producers within the region, energy will be exported from the energy storages. If the energy storages are empty or the stored energy is not sufficient to cover the demand, energy will be imported from the external power grid. Alternatively, energy will be exported to the external power grid, if the demand falls below the energy production inside Bavaria and the energy storages have already reached their maximum capacities.

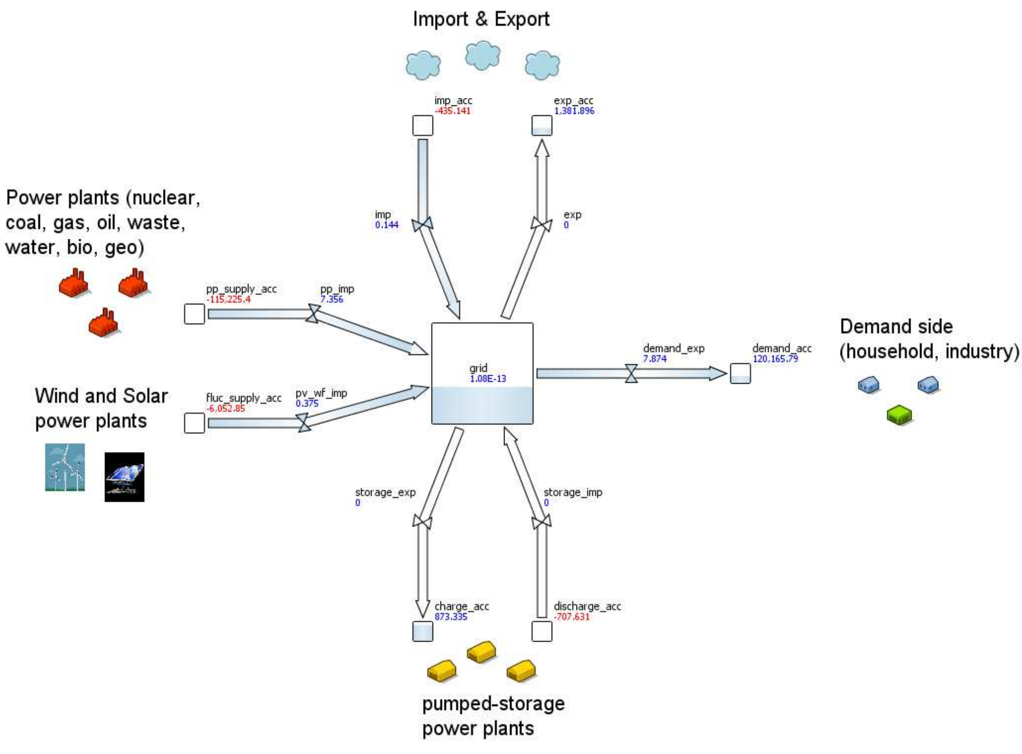

Figure 2: Main view of the simulation model in AnyLogic

The overall model logic can thus be summarized as follows:

From a recorded demand profile a fluctuating load is computed by applying stochastic impairments on the recorded values.

Renewable energy sources get highest priority to feed in and thus reduce the load in the model. Non-fluctuating sources (water, biomass and geothermal) feed constantly in, whereas fluctuating ones (wind, solar) depend on a wheather model.

The recorded demand profile is used as a load forecast. From this forecast and the feed-in from the renewables a residual load is computed which is the basis for the planning of the remaining power plants. The effects of the merit order are taken into account, leading to precedence order of nuclear, coal, waste, gas and oil. According to physical reasons we furthermore assume that the nuclear power plants are always allowed to feed in.

The feed-in from the planned power plants is substracted from the residual load. Forecast errors and possible under- and overload situations lead to a non-zero balance. A compensation is first tried by using the pumped-storage hydroelectrical plants by respecting their power and capacity constraints. If that is not possible, im- and exports to and from the environment are used in a second step to get a zero balance.

Please note that this is an abstraction of the behavior of the actual electrical energy system in which the merit order is performed on the German and even European scale and not just for a federal state. By considering im- and exports also as part of the merit order this will be taken into account in the future. At the moment the model allows to investigate how much the state is dependent on the environment. Resulting im- and exports are indicators of this.

3.2 Non-fluctuating Sources

The model for non-fluctuating power plants is constructed as follows. Figure 3 shows the typical structure of a conventional power-plant model.

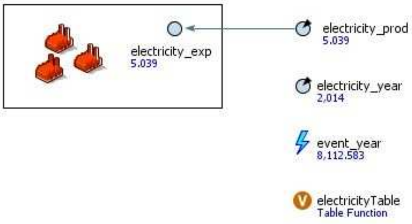

Figure 3: Model for a power plant

A non-fluctuating power plant delivers a constant power (electricity_exp) in GW or can switch on or off as needed (to simplify matters no physical contraints for switching on and off are considered). Because of the nuclear phaseout and the enlargement of gas or biomass power plants the available power can change every year (event_year). A specific plan for extension or reduction of the power of a specific power plant is modeled according to [Bay11] and explained in more detail in Section 4. In future work, we intend to model the load gradients, minimum downtimes and minimum operation times of conventional power plants.

3.3 Fluctuating Sources

We consider two different fluctuating sources in the model – solar and wind energy. For the solar module model, a solar insolation model is implemented according to [MZC09]. At the moment we distinguish between months and four days with different solar insolation values in quarter-hourly resolution. An overview of the implemented solar insolation model is shown in Figure 4. Moreover, Figure 4 depicts an example for discrete-event simulation. One of the four different weather profile days (sunny day, cloudy day, etc.) is chosen by a discrete event every 24 hours.

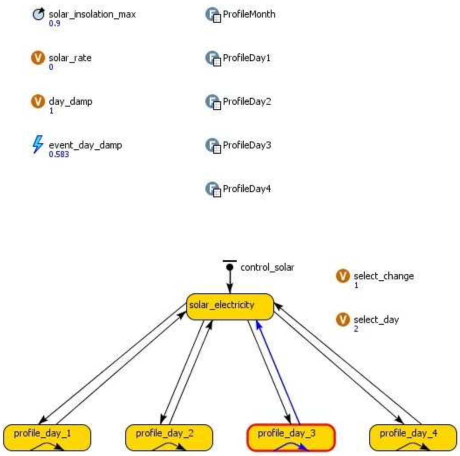

Figure 4: Solar insolation model

To simplify matters every photovoltaic power system is irradiated with the same solar insolation. The annually changing size of installed photovoltaic capacity is defined by a table function and is related to [Bay11].

For the wind farm model, a wind speed model is required. This model is quite similar to the solar insolation model according to [MZC09]. In contrast to the implemented solar insolation model, mentioned above, we use time series for wind speeds from a weather station in Bavaria near Munich (c.f. [Wun12]). All in all we consider four years of wind speeds in five-minute resolution separated into annual quarters and superimposed with a normal distribution to obtain different time series for wind speeds (see Figure 5). Finally the wind speed is transformed to a hub height of 80 meters.

To simplify matters again, every wind power station is operated with the same wind speed. At the moment we distinguish between two different wind power stations in the wind model. The already installed power stations have a maximum performance of

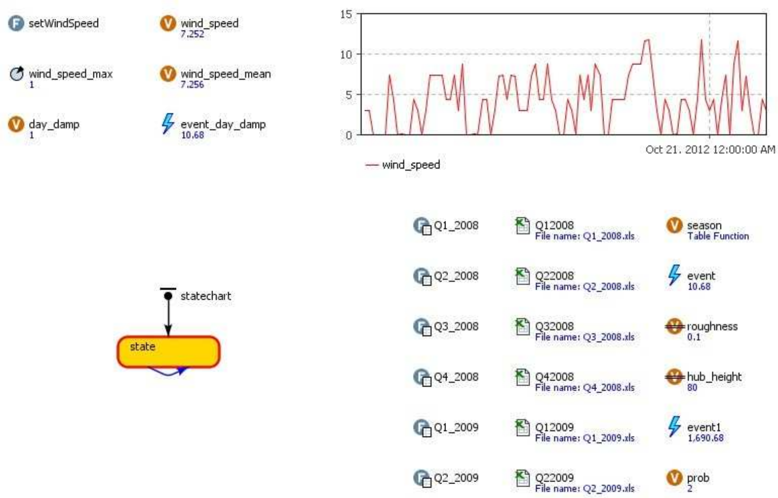

Figure 5: Wind speed model

1 MW, whereas new wind power plants have a maximum performance of 2 MW. The annually changing size of installed wind power plants is defined by table functions and related to [Bay11]. A typical power curve as a function of the wind speed is shown in Figure 6.

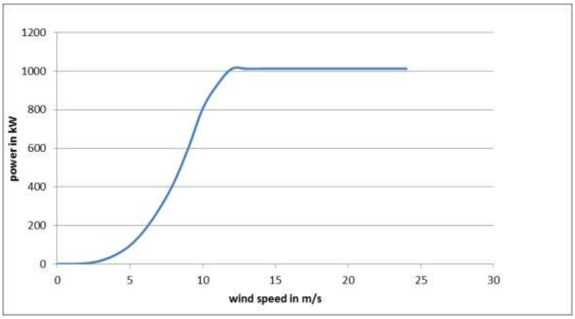

Figure 6: Power curve of a 1 MW - wind power plant

3.4 Demand Model

The demand model consists of an aggregate load profile according to [Alt12]. The load profile is differentiated by 50 percent housholds, 10 percent small companies and 40 percent heavy industries. The aggregated load profile is normalized to an overall energy consumption of 85500 GWh per year (c.f. [Bay11]) and superimposed with a normal distribution. Moreover we distinguish between different seasons and different days of the week. The different load profiles are implemented in a resolution of fifteen minutes. Figure 7 shows the fundamental setup of the demand model. The typical days (workday, Saturday, Sunday) are implemented as table functions and chosen by a discrete event (next_month).

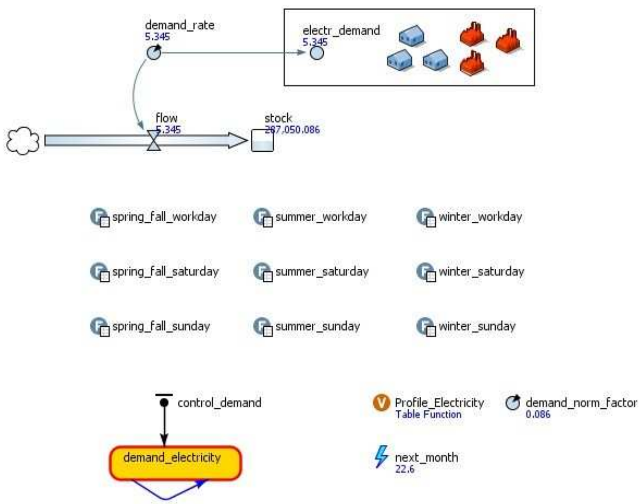

Figure 7: Demand model

In order to obtain a demand forecast, we use the same load profile without overlaying the current value with a stochastic function (see Figure 8). On the basis of this demand forecast profile we control the coal, waste, gas and oil power plants, i.e., we implicitly assume a perfect weather forecast.

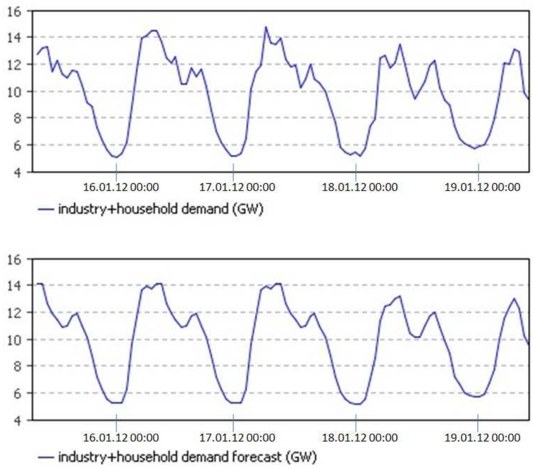

Figure 8: Aggregate load profile of four days with stochastic superimposition (top) and without stochastic superimposition (bottom) [x-axis: time in hours; y-axis: power in GW]

3.5 Storage components

As one energy storage component a pumped-storage hydropower plant model is implemented. The degrees of efficiency, maximum storage capacities and maximum power are considered. Figure 9 depicts the system dynamics model of a pumped-storage hydropower plant. The rectangles correspond to stocks for the current fill level (energy), imported (agg_imp) and exported (agg_exp) energy. Arrows represent energy flows influenced by different parameters like efficiency or capacity.

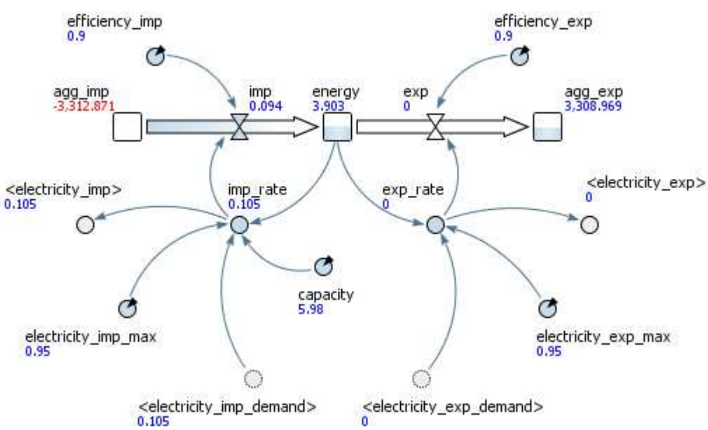

Figure 9: Model of a pumped-storage hydropower plant

4 Scenarios

In this section we describe one fundamental scenario which is inspired by the Bavarian energy concept [Bay11]. In this scenario the electricity demand should be covered by power plants within Bavaria as long as possible. The whole German electricity market is not yet taken into account, whereas we consider already the use of conventional power plants with regard to the merit order (precedence order of nuclear, coal, waste, gas and oil). Moreover, we turn our attention to one sub-scenario with respect to a different extension plan of pumped-storage hydroelectric plants.

4.1 A Scenario with Energy Storages

As mentionend above the plans are to enlarge renewable energy sources faster than previously thought. In 2021 50 percent of the Bavarian demand for electricity should be covered by regenerative energy sources. On the basis of [Bay11] Table 1 shows the status quo and the target state of the Bavarian energy mix in 2021. We have to keep in mind that the last nuclear energy power plants in Bavaria (Gundremmingen C and Isar 2) will be decommissioned by the end of 2021 and 2022, respectively. Moreover there is no indication of the development of coal, oil and waste consumption in the energy concept. Therefore, these fuels are assumed to stay constant.

Table 1: Extension plans

	Status quo (2009)	Target state (2021)
	Production in GWh	Production in GWh
Nuclear energy	51.971	ca. 22.600
Coal	4.434	ca. 4.800
Gas	9.325	ca. 23.900
Oil	2.145	ca. 2.140
Waste	528	ca. 540
Wind power	557	ca. 8.500
Photovoltaic	2.555	ca. 10.150
Biomass	5.881	8.000
Hydropower	12.500	14.500
Geothermic	n/a	2.400
Others	921	n/a

For our simulation model we linearly interpolate the extension plans for wind power, photovoltaics, biomass, hydropower and geothermal energy. After reaching the target state, the annual production of each source is assumed to stay constant. For example Figure 10 shows the extension plan of biomass energy in GW. Furthermore, we take five new gas power plants with a particular power of 800 MW into account (although it is subject of a debate whether such power plants can indeed be realized). The first one will be built in 2016 and the last one in 2023.

Table Data:

Argument	Value
2009	0.98
2010	0.905
2011	0.931
2012	0.958
2013	0.984
2014	1.01
2015	1.037
2016	1.064
2017	1.0899
2018	1.116
2019	1.1426
2020	1.169
2021	1.195
2022	1.195
2023	1.195
2024	1.195

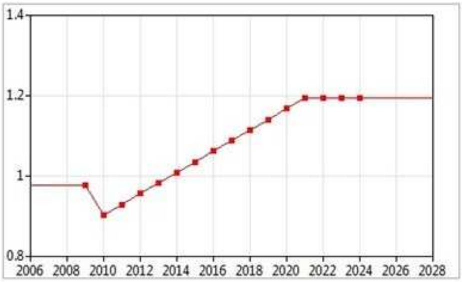

Figure 10: Linear interpolation of the expansion path of biomass in GW

The annual Bavarian demand for electric energy is assumed to be constant on a level of 85500 GWh per year. In [Bay11] it is also mentioned that the capacity of pumped-storage hydroelectric plants will be expanded from approximately 3.35 GWh in 2009 to 13 GWh in 2022. This extension should contribute to an agreed Bavarian energy balance and should guarantee the safety of the energy supply in Bavaria.

4.2 A Scenario without the Extension of Pumped-Storage Hydroelectric Plants

As a second scenario we consider the same scenario without the extension of pumped-storage hydroelectric plants and assume that the number of pumped-storage hydroelectric plants is constant over the next ten years. Hence the installed power of pumped-storage hydroelectric plants remains constant at a level of 3.35 GWh. The extension plans of renewable energy power plants can be taken from Table 1.

5 Results

This section considers the different scenarios described in section 5 with regard to the electric energy imports and exports of Bavaria. We investigate the annual energy balance according to the different scenarios. The simulated time begins on 01.01.2009 and ends on 31.12.2030. The simulation needs just a few minutes on a normal PC for one single run. The results appear representative according to our experience with the model, nevertheless independent replications and confindence intervals will be used in the future.

Figure 11 shows the annual electric energy im- and exports of Bavaria between the years 2016 and 2030. As we can see, a nearly balanced energy balance would be achieved, if the scenario described in subsection 5.1 would put into practice. It only remains a gap between 300 and 400 GWh of electric energy which has to be imported from the external electricity net.

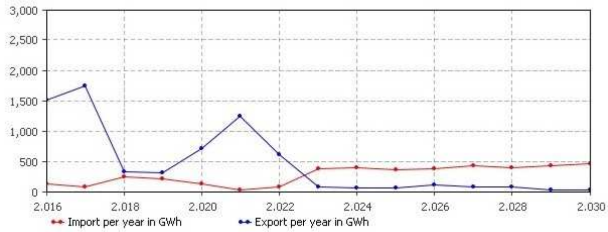

Figure 11: Simulation of the scenario with energy storages

It should be noted that those im- and exports are mainly related to peak load effects. The remaining gap between the yearly demand of 85500 GWh and the planned production is filled by an extended operation of conventional power plants.

The simulation of the annual electric energy im- and exports of the scenario described in subsection 5.2 is illustrated in Figure 12. As we can see the annual energy balance is quite similar to the previously described scenario. The annual im- and exports are higher, but the difference between eletric energy im- and exports are quite similar after 2023. As in the previous scenario, the other gap is filled by extended conventional production.

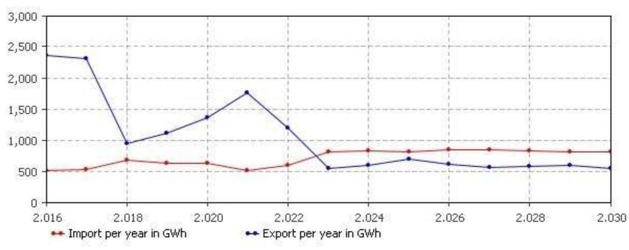

Figure 12: Simulation of the scenario without the extension of pumped-storage hydroelectric plants

6 Conclusions and Future Work

In this paper we presented a first version of a simulation model for analyzing the energy system on a scale of a federal state of Germany. We have described the different models for conventional power plants, fluctuating producers, volatile demands and energy storages and have given an overview of the interaction between the different components. Moreover, we have defined two main scenarios guided by the Bavarian energy concept to investigate the gap between annual im- and exports from the external electric energy net according to different extension plans of pumped-storage hydroelectric plants.

With the presented model it is possible to study different scenarios on a larger scale. Furthermore, it can be examined whether the extension of pumped-storage hydroelectric plants can help to ensure the safety of supply within an energy system with a high ratio of renewable energy sources.

We are planning to refine the simulation model in various directions. A coupling with a micro simulation model for photovoltaic and wind energy with a higher regional resolution is conceivable. As mentioned above, a more realistic model for conventional power plants is in progress. Moreover, we want to implement more load courses for different power plants and an electric energy net structure between the different administrative regions of Bavaria as well as the net transfer capacities to neighbouring states and countries in order to respect transmission constraints and losses. This will allow a better modeling of the interaction with the environment via im- and exports. We also want to take into account a better model of the energy market. Furthermore we want to investigate different storage technologies such as decentralized batteries or the methanisation of electric energy.

Ackowledgements

The authors would like to thank Dr. Klaus Hassmann for coordinating the "energy system analysis"-project and for the various discussions with him and the guidance from the participating companies.

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