An Agent-based Model for Simulating Smart Grid Innovations

Philippe Schädler
School of Business,
University of Applied Sciences and Arts
Northwestern Switzerland
Riggenbachstrasse 16,
4600 Olten, Switzerland
ph.schaedler@gmail.com

Holger Wache
School of Business,
University of Applied Sciences and Arts
Northwestern Switzerland
Riggenbachstrasse 16,
4600 Olten, Switzerland
holger.wache@fhnw.ch

Emanuela Merelli
School of Science and Technology,
University of Camerino
62032 Camerino, Italy
emanuela.merelli@unicam.it

***Abstract*—In order to derive indicators for the future grid and market stability, in this paper an agent-based model is introduced, to simulate various scenarios. This includes new market designs, market mixes, emerging technological inventions and new regulations. Consumers demand energy based on seasonal variations or changing prices. The suppliers' production might also depend on seasonal variations, on the local solar irradiation or its flexibility; the ability to react to the market requests. The model introduced in this paper has been used to describe an example scenario of the year 2035, representing a market mix that includes a variety different consumers and suppliers. Eventually it shows, how the model can be applied to model various scenarios and how the resulting grids frequency, the market prices and suppliers profit can be used as indicators for the grid and market stability.**

***Index Terms*—Agent-based simulations, energy markets, short-term simulations**

I. INTRODUCTION

The main objective of the Swiss Energy Strategy 2050 is to replace nuclear power-plants with more distributed renewable alternative energy sources. This transition will not only have an impact on the electricity grid, but also on the energy markets [1]. This is amplified by the large amount of market participants, their interactions and the fact, that the influences of new innovations in technology and business models are unknown [2].

If the suppliers of basic supply are not able to produce economically, the balance of supply and demand is endangered. Missing historical data and disruptive innovations lead to an unpredictable market behaviour and an uncertain grid stability [3]. Furthermore, changing behaviour of customers and alternative markets models increase this uncertainty. Additionally, new regulations or changes to the infrastructure have to respond fast in order to avoid blackouts or extraordinary prices [4]. For this, an agent-based model has been developed to analyse and compare different scenarios. Agent-based models enable simulations where no historical data is available and have been successfully applied for studying different behaviour of electricity market and large-scale simulations. But current models were not focusing on both the grid and market stability of future energy mixes, but rather to analyse the price impact of different implementations, or to support current decisions based on large-scale models [5] [6] [7]. Therefore the agent-based system presented here focuses a related market and grid on a fine–grained simulation and includes dynamic behaviours of their participants.

Consumers react on price changes, and change their demand based on the daily and seasonal use. The supply side varies on an annual cycle, and its price is based on fixed and variable costs. The suppliers' flexibility is often neglected, even if the learning behaviour strongly influences the final solution. As this leads to a grid imbalance, flexibility is especially important to be considered in the model.

II. MODELLING

In this paper a model is introduced, that doesn't require market participants to follow the market outcome. The grid is therefore not perfectly in balance and charges are fined for causing imbalance.

The market is planning a perfectly balanced, economical system based on the energy-only market with merit order but the actual (physical) balance is based on not-following this planning, for this the imbalance market takes place. In order to analyse the impact of a scenario to the market and grid stability, the imbalance market is only considered on the economical level. This means, that only a single energy-only market will be modelled in order to see the whole impact and a bookkeeper punishes the physical imbalance.

A. Architectural Design

The architectural design of the model adapts the framework of [5], which combines successful approaches of agent-based modelling of electricity markets. The model consists of six elements or sets of agents as shown in Figure 1, and its environment. The agents' interaction is defined by the arrows. The agents' communication follows a strict order as some actions depend on information provided by other agents. During the *preparation phase* (dashed line) the price is determined based on the expected usage, while during the *real-time phase* the actual usage is defined.

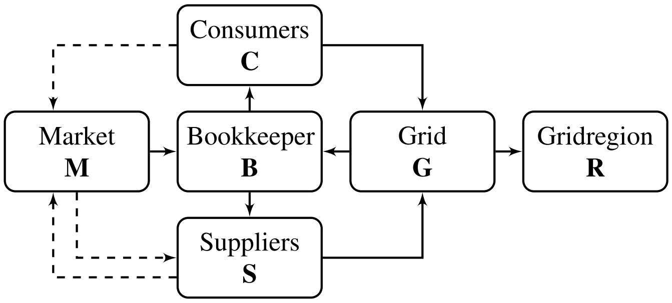

Fig. 1. Architectural Design

The sets of agents are described as follows:

Consumer (C) Consumers define the total demand of the whole system, and thus define the required amount of produced energy. A consumer sends a demand notification, to indicate the expected consumption.

Supplier (S) Suppliers produce the energy. They sends an offer and might receive an order back from the market. The subsequent grid interaction is then completely independent of the received order.

Market (M) The market defines the market processing method. Based on the demand expectations and received offers, the markets' task is to send the orders to the suppliers and define the market prices.

Bookkeeper (B) Bookkeepers manage the settlements and ledgers. Based on the produced or consumed load, revenue or expenses are generated. Depending on the differences between the actual and expected grid utilization a penalty fee is additionally charged in order to penalize wrong behaviour (economical part of a balancing market). It eventually sends the payment or deduction to the suppliers and consumers.

Grid (G) The grids usage can vary from the market expectations, as the actors send their load directly to the grid. The grid is collecting and forwarding the usage to the bookkeeper and the grid region accordingly.

Grid Region (R) The grid region is the physical interconnected grid of all grids. It's main purpose is to provide overarching grid information, like the frequency – which is the main indicator for the grid stability.

B. Environment

The environment represents the agents' information exchange. A single state of the environment is thus represented by the following tuple:

$$e = \langle T, \mathit{Of}, \mathit{No}, \mathit{Or}, \mathit{Pr}, \mathit{Pe}, \mathit{Tr}, \mathit{Ut}, \mathit{Fr}, \mathit{De}, \mathit{Su} \rangle$$

Every state of the environment has a time *(T)*, such that the actual hour, month and total run-hours can be derived from it. The time-management is provided by the environments state transformer function, and is perceived by the agents. [**?**] Every tick in the simulation represents one hour. But each hour consists of six steps, which has to follow a specific order.

The table I shows which agent provides which part of the environment at which step. The steps are denoted with Roman numbers, and each of the steps represents an individual state.

The bookkeeper publishes its penalties *(Pe)*, such that the suppliers and consumers are able to evaluate the risks appropriately. Offers *(Of)* are provided by the suppliers **(S)** and are the basis for the markets orders. All consumers **(C)** send their expected demand *(No)* via a *notification* to the environment. The sum of all expected demands of an environments state is the basis for the markets definition of the orders and the prices. The orders *(Or)* and market price *(Pr)* are then sent to the suppliers. All transactions *(Tr)* are stored in the environment. The utilization *(Ut)* of the grid is based on the ledgers supply and demand, which is aggregated and combined into a single element. The frequency *(Fr)* describes the ratio between supply and demand in Hertz (Hz). The demand *(De)* and supply *(Su)* of this environmental state is then applied.

TABLE I
ENVIRONMENTAL INTERACTION PER PARTICIPANT.

Step	I	II	III	IV	V	VI
environmental state	e_{I}	e_{II}	e_{III}	e_{IV}	e_{V}	e_{VI}
T	*transformation*					
Of		**S**				
No		**C**				
Or			**M**			
Pr			**M**			
Pe	**B**					
Tr						**B**
Ut					**G**	
Fr						**R**
De				**C**		
Su				**S**		
Phases	Preparation			Real-time		

This model allows to not obey the market orders, which results in a deviation of the planned and actual production and consumption. This difference results in an instability which is indicated by the frequency and its volatility. It also allows chronological indicators, delivered by the grid region and bookkeeper. The set of agents which represents the market mix is described in the following section.

C. Grid Participants

Agents depend on information that has to be available in the environmental state in order to provide the next step within this simulation round. Additionally to the available data in the environmental state, parameters can be defined in order to adjust the agents behaviour and model a certain scenario.

1) Consumer: The *timed consumer* simulate different daily consumptions, including seasonal alternations. A combination of such agents with different usage-hours and quantities is used to model complex time depending consumers.

The objective of the *price elastic consumer* is, to react with a change in demand to a changed price. The price elasticity of demand describes how consumers change their buying behaviour based on a price change [10]. Therefore the expected demand varies from the actual demand, and no precise usage can be indicated when sending the notification.

2) Supplier: Suppliers are the counterpart of consumers and provide the energy demanded by the market. First, a supplier defines a price and an amount of energy which is packed in an offer. That package will then be provided to the environment, and accessed from the market. The agent can either follow the order or ignore it, depending on its own needs and its economical and/or physical constraints — but is then forced to pay a penalty fee.

From the requirements it can be derived that different suppliers have different properties. The following four agents have been designed: the *fixed supplier*, *seasonal supplier*, *photovoltaic supplier* and *proactive supplier*. All the suppliers use a linear cost function, based on a margin, fixed and variable costs.

A simple *fixed supplier* ignores the orders and does not have a perception; it always supplies the given amount. This agent's price is derived from its costs, margin and quantity of supply. The linearity ensures, that it is always the best option for an agent to produce the maximum possible amount.

The function introduced by the timed consumer is reused to get the seasonal variation for the *seasonal supplier*. These agents are useful model supplier that have seasonal supply variation hydro-power plants. They can also be used to model suppliers that have a cost function and always follow the order like gas-, geothermal- or biomass power-plants.

An example using a more precise formula for defining the supply variation is the *photovoltaic supplier*, which production function is depending on time and the current location. These agents simulate the daily dynamics of photovoltaic installations and shows exemplary how complex supply functions can be implemented.

All agents described so far had no need or no intention to avoid penalty costs. Either they just don't care, like the fixed supplier – which is useful to provide instability on the grid or the agent easily avoid the penalty by following the orders. A more realistic behaviour is, if the supplier is only able to react partially, then a partial overproduction occurs. This means, that the agent has to predict and act proactive to prevent penalty fines, for this the *proactive supplier* is introduced. The agents only additional parameter, compared with the fixed supplier, is a shut-down time, which indicates how long it takes to completely turn on, or shut-down the supplier. Within one tick it can only act a fracture of the total supply, which is defined by this shut-down time. The agent has three options before handing in the offer; it can either increase, decrease or not adjust the supply. In order to be able to perfectly follow an order, an agent which decides not to adjust the supply is able to follow the exact amount within the range of the shut-down time. The decision, which option is chosen is based on forecasting all three options and compare the end-results – the option which in total provides the best profit is chosen (including expected penalties, costs and market prices). Based on the chosen option, the future supply is defined. The price is then defined completely independent of the chosen option: As the agent can't directly follow the order, it has to adjust the price to avoid the penalties – even if the price is temporary below the production costs. For this, the agent learns the hourly prices, predicts an expected price and approximates it by increasing its offered price step-by-step. If the offer was accepted (which is indicated by a received order), the agent notices the success and increases the price in the next round. If the offer was not accepted (no order has been received), the agent will learn the failure and reduce the price. As described in the market, there is also the possibilities that an agent only receives a partial success if only a part of the offer was ordered. It is then not adjusting the price, in order to prevent underbidding – but is learning the amount ordered for that particular hour. This knowledge is then used to evaluate the expected overproduction and included in the comparison of the best options. A partial success is not considered as a success or failure, such that the price remains the same. This agent can be used to simulate power-plants that have a technical flexibility constrains, like the nuclear or coal power-plants.

The *trading prosumers* buy and sell energy if they assume to be able to sell it later for a higher price. It also should only feed-in the supply if the offer was accepted. The buying behaviour is implemented using a short-, and long-term moving average of the price. The price is evaluated on the storage value and a margin.

III. EXAMPLE

The example implements a fictitious mix that only aims to show the usage of the model. The market is applying merit order with uniform pricing. The implemented penalty configuration equalises the overproduction and underconsumption and additionally penalises underproduction and overconsumption.

A. Set of Consumers

The electricity demand is defined by the consumers and split up in the four main consumers *services*, *traffic*, *industry* and *households*. It is assumed that *services* consume 17.5 TWh, which is more-or-less equal to a 2 GW static *Timed Consumer* which runs for the whole year, and that these consumers are not affected by the price or the seasonal variations. *Traffic* is also expected to have a continuous annual usage of 7.5 TWh, which is 0.856 GW: It is assumed that industries also constantly require energy, but according to [11, 3], they might change the demand in a short time span. As an estimation, the highest measured households price elasticity of -0.4 was taken, while a reference price of CHF 0.20 is used. A group of five agents of the *Timed Consumer* design a daily and annual distribution of consumption of 1.725 GW.

It is further assumed that only 1.75% of the households have a smart meter and an energy storage with 20 kWh per household. This can be represented by a single *Trading Prosumer* with a throughput of 30.0 MW and capacity of 2 GWh. This results in an assumed total annual consumption of 58 TWh for the year 2035.

B. Set of Suppliers

This example model represents an even more optimistic scenario with a total of 40 TWh hydro-power production. The run-of-the-river hydro power-plants produces around 50% of the annual 40 TWh, which is equal to 2.283 GW, while the production during the summer is usually around 38% higher, an even bigger difference of 86% is modelled in this scenario. Production costs of CHF 0.145 are assumed. The variable production costs of hydro-reservoir is assumed to be CHF 0.245.

For the pumped-storage power-plants in this scenario an value 0.340 GW is assumed.

For this scenario it is assumed, that still one or two nuclear power plants with a total supply of 1’500 MW are not yet turned off and able to produce 13 TWh annually. The variable costs of a nuclear power-plant are assumed as CHF 0.06 per kW. It is also assumed that it takes linearly 12 hours to shut-down the plants, with approximately fixed costs of CHF 20’000 per hour . The example scenario thus assumes a total production of 2.5 TWh, which is on average 285 MW of effective production capacity; meaning that the installation must provide around 2.6 GW. If also a price of CHF 1’500 per installed kW is estimated, over 30 years an hourly price of CHF 15’000 is assumed. For the example scenario, an unforeseen price drop is simulated. Guessing that the investment costs of CHF 15’000 are reduced by 90% to CHF 1’500.

Two additional examples are introduced, the *gas / combined-cycle power-station* and *coal power-plant*. The investment costs are assumed to be between CHF 800 and CHF 1’300 per kW and 0.16 CHF variable costs per kWh for *gas / combined-cycle power-station* and a p potential of 15 TWh for 2035. For both plants only 400 MW are considered, with hourly fixed costs of CHF 1600. This *gas / combined-cycle power-station* has a shut-down time of 2 hours and an assumed price of 0.15 CHF. The *coal power-plant* has an assumed shut-down time of 6 hours but at a lower price of 0.15 CHF.

For the proposed model, the *import* is the last available resource, which can be seen as a producer with almost infinite capabilities. Thus, the import defines the upper limit of the price range, which is given as CHF 0.30 with a 10% margin. This can either be represented using a static *Seasonal Supplier*.

C. Evaluation

For the agent-based system the Repast Simphony Framework has been chosen, being the the most popular framework for developing *agent-based models* [8].

1) Grid Stability: The simulation for providing data for evaluating the grids and markets stability ran for $17'520$ ticks, which represents two years, starting at January 1st 2034. Since no further initial states are configured, the agents have a whole year, to adapt to the annual changes and fill their capacities. The following has been observed for the year 2035. The standard deviation of the frequency indicates its stability. The average frequency is 52.877 with a standard deviation of 4.24. This value can’t be compared with Swissgrid, as Swissgrid calculates and compares the standard deviation of periods of 15 minutes as mentioned in the literature review. The total value range is between 44.871 and 69.997; the first quartile is exactly at 50, while the third is at 55.176 – which gives an interquartile range of 5.176. The median lays at 50.766. Apparently, there is a constant over-production – in 75% of all the ticks, the supply was higher than the demand. This can be due to the fact, that the agents only offer what they are able to produce, but sometimes without receiving the order. This implies that orders always can be followed. In the current model, agents are able to follow the order if the offer is higher than the order, but not the other way around. It is assumed, if some uncertainty on the supply side would be implemented, the frequency would be more evenly distributed.

2) Market Stability: Analysing the market stability by looking at the distribution of the price, it can be seen that the average price lays at CHF 0.278 with a standard deviation of 0.041. The maximum price was observed at 0.33, the minimum at 0.146. The median price is located at 0.255, while the first and second quartile are at 0.247 and 0.33; which gives an interquartile range of 0.083. Apparently, at least 25% of all the defined prices, made use of the import agent, as this provides the upper price limit of 0.33.

Figure 2 and Figure 3 show the average price per hour and per day. The daily distribution shows lowest prices at 3 pm. Since the two peaks occur mostly in the second part of the day, the daily distribution shown in Figure 3, presents a higher price in the evening.

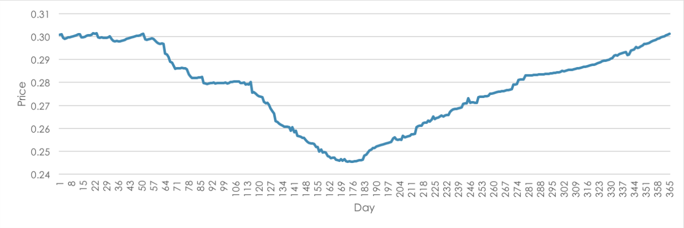

Fig. 2. Average Price per Day.

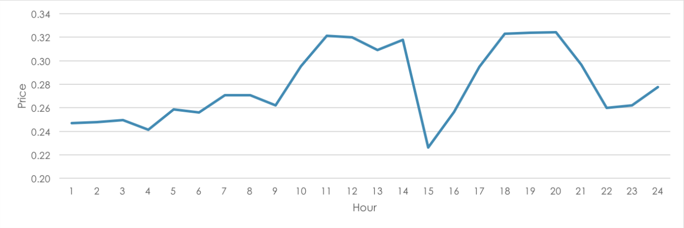

Fig. 3. Average Price per Hour.

Other indicators for the stability can be retrieved from the ledgers, by looking at the profit of the market participants. Table II provides this compilation and shows that every supplier has a positive balance – even the traders, which means that the agents’ behaviour successfully invests and sells. It also means that a hydro-power-plant, which are expected not to be profitable, seem successful in this model. The total profit is around CHF 7 billion. The most successful supplier is the hydroelectricity run-of-the-river, making around 37% of the total profit, or CHF 2.6 billion. According to the configuration, hydro-power provided from reservoirs would have been able to provide the same amount of supply, but for a much higher price. A total of 62'115'669'326 kWh was supplied, 57% of that is produced by hydro-power plants. Here, the profit of the photovoltaics supply is very impressive: with only 2.5 TWh, CHF 678 million profit were made, which is a margin of CHF 0.279 per kWh (the average margin is CHF 0.113 per kWh). This is explained by the very low investment costs while setting up the scenario. A table showing the supply per participant and hour is provided in the appendix.

TABLE II
ANNUAL PROFIT AND SUPPLY.

	Profit (CHF)	Supply (TWh)
Hydro. - ROR	2'602'539'957.89	19.997
Nuclear Power	1'961'287'521.18	12.827
Hydro.-Reservoir	693'249'131.53	15.442
PV	678'887'991.07	2.432
Coal	428'815'478.72	3.455
Gas & CCPS	397'086'098.13	3.358
Hyrdo.-Pumped-Storage	174'845'820.77	1.201
Import	98'784'956.59	3.307
Smart Meter	15'405'489.58	0.098
Total	7'050'902'445.45	62.116

As shown in Table III, eventually 58.955 TWh have been consumed while 58 TWh were actually planned. Traders have influenced this statistics by additionally consuming and storing 1.594 TWh. The price-elastic industries have compared their usage to a price of CHF 0.20. The industries actual consumption was therefore reduced from 17.52 TWh to 14.79 TWh. All households combined consume largest part as shown in table III, including the Smart Meter. With a total consumption of 17.59 TWh, their demand exceeds the expected 15.125 – apparently the applied rounding while distributing the load to several agents was quite unfortunate. The services and traffic exactly match the expectations.

TABLE III
ANNUAL CONSUMER EXPENSES AND DEMAND.

	Expenses (CHF)	Demand (TWh)
Households	5'305'502'497.50	17.550
Services	4'866'755'043.36	17.520
Industrial Consumer	4'133'878'207.04	14.793
Traffic	2'082'971'158.56	7.499
Hydro.-Pumped-Storage	430'720'257.28	1.496
Smart Meter	27'184'412.65	0.098
Total	16'847'011'576.38	58.954 kWh

Comparing the demand and supply of the traders, the remaining capacity can be observed. The smart meters, consumed and provided an equal amount of 97.58 GWh, which means that its capacity was empty when the simulation stopped. The hydro-power pumped-storage bought 295 GWh more than consumed, which means that this part must be still stored. The total capacity is 1.25 TWh, which means that the storage usage filled around 23.9% through the year.

IV. CONCLUSION

It has been shown how an agent-based model has to be modelled such that it can represent scenarios of Switzerland's future energy market. In an example scenario, based on a mix of today's expectations about a future market and grid, the agents was configured to represent different participants. Their interactions have been observed and analysed. Based on the literature review, today's and future market and grid participants were derived, which gave the foundation for an abstraction of the model's agents.

The *market* behaviour was defined by the algorithm, how the orders are placed. The *grid* interactions are completely independent of the *market*, but the differences are noticed and considered by the *bookkeeper*. The variety of actions of the market participants can be allocated to *suppliers* and *consumers*.

It was shown how the resulting data can be analysed, and thus allows the comparison of scenarios. The comparison is basically based on the five-number summary of the frequency and price which provides basic information about the datasets and the regression analysis of the price and frequency through the whole year. The provided frequency won't directly indicate the actual frequency of 2035. It rather shows the influence of the Swiss market, without any safety net to the stability of the grid. The same is valid for the price, thus the model is indicating possible distributions based on different parameters. Eventually, also the profit of all participants has been compared. It has been shown that an agent-based system can be modelled in a way, such that it is capable of simulating scenarios of the Swiss energy market of the year 2035, considering the behaviour of participants of market mixes according to today's expectations, in order to derive indicators for the future power grid and energy market stability.

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