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Toward Real Options Analysis of IS- Enabled Flexibility in Electricity Demand

by

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Abstract

As the transition to wind and solar progresses, the integration of renewable energy sources makes electricity production increasingly fluctuating, also causing volatility in electricity prices on energy markets. In order to guarantee power grid stability, utilities need to balance volatile supply through shifting demand. This measure of demand side management creates flexibility, being enabled as the integration of information and communication technology, e.g. smart meters and load control switches, in the power grid grows. The flexibility of deferring consumption to times of lower demand or higher supply bears an economic value which can be quantified by recurring to electricity market prices. Our kernel theory in terms of design science research, real options theory is the appropriate approach for quantification under uncertainty. It provides for the assessment of investment potential in information systems for load control. Addressing the prerequisite, we develop a stochastic process which realistically replicates electricity spot price development. In further research, we will thereby assess the value of IS-enabled flexibility in electricity demand.

Keywords: demand side management, load shifting, economic value of IS, electricity spot price model, real options

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Introduction

Faced with growing environmental concern, several countries aim at transitioning their power supply from fossil and nuclear sources to renewable resources, such as solar and wind. The shift toward these intermittent resources makes electricity supply increasingly fluctuating (Feuerriegel et al. 2012). As a sole reaction, adjusting the supply curve through electricity storage would not be sufficient—neither to balance highly volatile supply and demand, nor to offset the involved strain on the power grid. Electricity supply features peaks, e.g. by non-forecasted gusts of wind, as does demand. Both has stimulated the idea of intervening on the demand side as well (Palensky & Dietrich 2011).

Activities influencing the timing and magnitude of consumer demand for electricity with the purpose of accommodating fluctuations of electricity production have been referred to as demand side management (DSM) in business research since the 1980s. Demand response (DR), another common term, is considered a subclass of DSM measures with voluntary participation (Palensky & Dietrich 2011). For our approach, we use the term DSM, which we define as the entirety of activities influencing the timing and magnitude of consumer demand for electricity. An IT enabler for DSM is advanced metering infrastructure (AMI), the totality of systems for measuring, collecting, transmitting and analyzing energy usage data. AMI combines smart meters, which measure electricity consumption in time intervals, and bidirectional communication streams between utilities and consumers (Callaway & Hiskens 2011; Li et al. 2013). Utilities can remotely control demand, in particular emit control signals via AMI to initiate the deferral of electricity consumption to times of higher supply or lower demand, so-called load shifting (LS).

The tools to shape demand provided through DSM do come at a price: first, utilities will need to “buy” the flexibility being granted—they need to compensate consumers, who give away the right to have their appliances at their complete disposal, for approving LS measures. Utilities could make them dynamic compensation offers in real time. Second, utilities will need to invest in information systems (IS) that provide the transmission medium for signals and information, support decisions on when to shift loads, initiate and control the process. Hence, to reach profitability, there is the need for methods to quantify the economic value of individual LS measures in consideration of electricity market information. Such will help to decide on short-term compensation offers and surplus funds available for technological investments on a level of consumer supply. A further motive is to save the dispatch of expensive back-up reserve, which is possible when LS enables utilities to control peaks of consumption. In our vision, every time loads are signaled to be deferrable, utilities will be able to determine how much shifting them over the course of some hours is worth in money. Intensified by the expansion of smart grids and AMI, the opportunities for applying DSM and deploying its capabilities for a sustainable energy transition will grow.

The first step toward a method capable of identifying times for profitable LS and its monetary quantification should be finding a suitable valuation technique. Applicability to real-world cases is given when the model, firstly, is fit for processing electricity prices as the key information. Secondly, it needs to be operable when the price development of electricity is uncertain, over the course of a few hours. Equipped with a proper algorithm, decision support systems (DSS) could determine times when LS bears a value.

The flexibility a consumer offers to a utility can be regarded as an option to shift loads; it enables the utility to decide at each point in time whether to deliver the load immediately or later. To determine its value, option valuation methods come into consideration. Particularly, with electricity as a tangible, non-financial product serving as the underlying, we suggest assessing the option’s value by means of real options theory, a method to evaluate flexibility in a condition of uncertainty. In order to prepare its application, there is a need for research on a stochastic process model which replicates electricity spot price movement, as closely to reality as possible. This model would provide for an according algorithm to be integrated into DSS.

Hence, from the overarching research objective described above, we derive our research question:

How can electricity price movements be described by a stochastic process that accounts for their existing uncertainty, and allows for real options analysis (ROA) of IS-enabled flexibility?

Our research objective covers a relevant real-world problem, as an answer could facilitate profitable LS decisions. We apply design science research (Hevner et al. 2004) to develop an artifact that is generally applicable to various electricity markets worldwide, for example those in the United States and Europe. We process electricity prices as the key information. In many scenarios our artifact thus needs to cope with a condition of uncertainty: LS comprises the course of some hours (i.e., intraday), over which price

development is uncertain. In the course of our search process, we set up a stochastic model for the underlying's price, thereby addressing a prerequisite of ROA (Ullrich 2013). It realistically captures electricity spot price development in most market situations, yet is straightforward to apply. Such a stochastic process successfully replicating real-world spot price development, makes ROA flexible to be applied in most market environments and situations.

This research-in-progress paper is structured as follows: In section 2, we discuss related work. In section 3, we give a summary of our methodology. We then explain our data set and conduct some helpful data evaluation. On this basis, we develop an appropriate stochastic process for describing electricity spot market prices based on the concept of a geometric Brownian motion. Section 4 concludes our paper in addressing limitations and giving an outlook on further research.

Related Work

Preparing ground for flexibility valuation in IS-supported DSM is a contribution to energy informatics (EI): as a subfield of IS research, EI should apply “information systems thinking and skills to increase energy efficiency” (Watson et al. 2010). We address this claim with our objective to improve the integration of electricity price information with IS for load control, in order to increase the efficiency of energy demand and realize economic potential. Watson et al. 2010 suggest finding practical solutions, which a spot price model applicable to intraday decisions is. Goebel et al. 2014 argue that effort toward quantification of the relationship between IS-enabled DSM and realizable economic impact is needed. This type of EI research is essential in order to enable decisions on technology investments facilitating LS on a level of consumer supply. As long as their economic potential is uncertain, investments in IS for load control like AMI will be missing, preventing that they deploy their capabilities for a sustainable energy transition.

Information and energy systems researchers have done well in addressing the issue of incongruent, highly volatile electricity supply and demand curves. Taking a design science approach, Bodenbenner et al. 2013 draft a DSM system orientated toward LS application. Strüker & van Dinter 2012 give a literature review on existing IS research contributions on demand response. They identify the quantification of the economic value as an open research question. Some papers have indeed prepared the ground for quantification of flexible consumer demand: Sezgen et al. 2007 address the need of quantifying “the economic value of investments in technologies that manage electricity demand in response to changing energy prices”. We consider the authors' analysis of an option-valuation methodology a very important contribution; however, their model is not capable of capturing intraday flexibility. The authors leave this to follow-up work.

Other scholars determine the value of flexible demand by taking simulation approaches: Biegel et al. 2014 not only describe requirements for aligning flexible appliances with the electricity spot market, they also give an estimate of the cost and revenue, which depend on the magnitude of demand. Feuerriegel & Neumann 2014, subsequent to Feuerriegel et al. 2013 and Feuerriegel et al. 2012, identify the need for quantification of DSM's economic potential. Based on statistical data, they derive an optimization problem for when to shift loads, which they evaluate in a simulation. Goebel 2013 investigates a particular case of DSM application: controlled charging of a fleet of plug-in electric vehicles. By simulation, the author finds that utilities with an intelligent charging schedule are able to secure a savings potential. From a reproduction of household load profiles, Gottwalt et al. 2011 conclude that “an individual household can expect rather low benefits of an investment in smart appliances”. We intend to supplement the work of these authors with a higher degree of generality by introducing a stochastic price model and standard valuation techniques.

Existing approaches to model electricity price development by stochastic means include the work of Schneider 2012. The author describes solutions to account for negative electricity spot prices in spot price modelling. He fits a complex stochastic process specifically to integrate negative spot prices into pricing models. We strive, however, for a model which is easier to handle in real-world application. Moore et al. 2010 conduct spot market price regressions on natural gas prices. Their forecast of long-term peak price distributions is not applicable to intraday spot price development, particularly in the electricity markets. Designing a financial instrument for the purpose of hedging against price risk in the electricity spot market, Oren 2001 uses a pricing model based on the assumption of a regular geometric Brownian motion process. The author concludes that the unadjusted model does not suffice to replicate electricity spot price development, leaving the formation of more realistic pricing models to further work.

Modelling Electricity Spot Price Movement

Methodological Summary

We suggest to assess a utility's flexibility to shift loads by the means of real options theory. In the terms of Gregor & Hevner 2013, it serves as the kernel theory to our artifact. Real options theory was derived from financial option valuation, which is a well-developed methodology. It has been implemented as ROA in numerous cases in IS research (Benaroch & Kauffman 1999; Ullrich 2013). So far, in the energy sector, ROA has been widely applied for the evaluation of electricity generation projects (Deng & Oren 2003; Martinez-Cesena & Mutale 2011). The capabilities of real options should also be used to evaluate a utility's flexibility to shift loads with respect to uncertainty in electricity prices (Oren 2001; Sezgen et al. 2007).

We picture reality by modelling a deferral option, which is an established type of a real option. For analytic assessment of its value, a stochastic process appropriately depicting the factors with influence on the underlying's price development is a prerequisite. First, it should incorporate the expectation for electricity prices by assuming that spot prices tend to drift toward their long-term mean (Benth et al., 2014). Such a process is called mean-reverting. Second, it needs to consider uncertainty in hour-to-hour returns: the underlying's price volatility is an essential parameter for option price valuation. As our artifact in this paper, we design a stochastic process fulfilling both prerequisites. In future research, it shall be transferred into the binomial model of Cox et al. 1979, which is a common approach for discrete option valuation, and allows dynamic decisions on LS in consecutive hours. This is the basis to quantifying the value of IS-enabled flexibility in electricity demand.

In the following section, we study historical spot market price data from the European Power Exchange (EPEX SPOT) to replicate their development. Trade on EPEX SPOT comprises power for the supply of four market areas: Germany, Austria, France, and Switzerland. Electricity for Germany and Austria is traded on a shared market, separately from French and Swiss markets. Like in many other power grids, electricity supply and demand for these countries are coordinated through market mechanisms (Umutlu et al. 2011). This is why understanding the trade of electricity contracts is essential for reaching our objective. Furthermore, we need to assume that electricity contracts can be used as purchased from the markets, with no transmission restrictions interfering.

Whereas utilities have secured medium- to long-term supply through power generation capacity, concluded supply contracts, or acquired futures contracts, ultimately they need to bring fluctuating demand in line with supply throughout the day. Short-term matching occurs through recourse to balancing energy, i.e. single-hour electricity contracts in day-ahead or intraday trade, and back-up reserve provided by generators (Biegel et al. 2014). Figure 1 illustrates these instruments. Due to their variability, the integration of renewable energy sources increases the demand for balancing energy. Dispatching back-up reserve is costly,

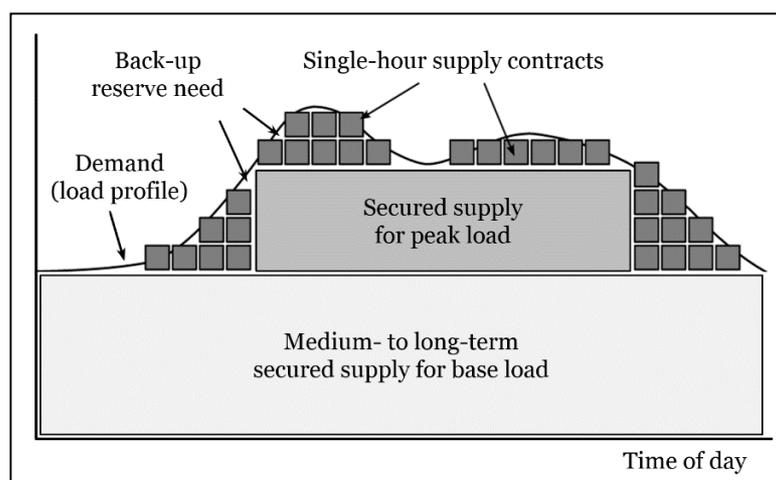


Figure 1. Market instruments for adjusting to consumer demand

being “compensated many times over the current spot market price and twice as high as the guaranteed feed-in tariff for renewable energy” in Germany (Strüker & van Dinther 2012). Hence, purchase of single-hour contracts is the preferred means for adjusting to fluctuating consumer demand in the short term. At the same time, this indicates that spot prices of single-hour electricity contracts are the minimum investment for supply adjustments in the short term. Hence, this type of electricity contracts is relevant to model LS scenarios. Whenever a utility seizes flexibility to defer demand to another point in time by means of AMI, it realizes the difference in spot market prices as a profit. In addition, this may prevent need of recourse to back-up reserve, which bears even higher economic potential.

Data Evaluation

The data set of this study is a time series of spot market prices from EPEX SPOT, which covers German/Austrian market areas and originates from Thomson Reuters Datastream. Our query has yielded final spot market prices for 24 hours on weekdays (Monday through Friday). Traded objects are single-hour physical electricity contracts, quoted in Euro per megawatt-hour (€/MWh). On EPEX SPOT, spot prices are initially set in auctions on the day before delivery, thereafter impacted by intraday trade on the spot market, up to 15 minutes before delivery time. A utility may acquire single-hour electricity contracts in either way. Encompassing recent ten years of spot market trade on EPEX SPOT, boundary dates for our analysis have been set to 1 June 2004 and 28 February 2014. We distinguish between three periods: summer, winter, and intermediate seasons (an ensemble of spring and autumn). Hence, within the span of the boundary dates passed 10 summers (Jun–Aug; 2004–2013), 10 winters (Dec–Feb; 2004/05–2013/14), as well as 19 intermediate seasons (Mar–May, Sep–Nov; 2004–2013).

From the obtained historical data, we establish an hour-to-hour time series of electricity spot market prices. Table 1 depicts descriptive statistics for these values. It is noted that, in the regarded timespan, 120 observed prices valued less or equal to zero. They have reached values as low as -222 €/MWh during Christmas 2012. The small flexibility of electricity production, restricted by technical and regulatory constraints, is the cause for negative prices (Schneider 2012). There may be times, for example, when a surge in wind power meets little demand for electricity, or delayed reduction of power plant capacity. Such times will prove especially valuable for fulfillment of shifted loads, when they become known through monitoring IS. On EPEX SPOT, negative spot prices for single-hour electricity contracts in German/Austrian market areas have been permitted since September 2008.

Season	Summer	Winter	Intermediate	Overall
Spot prices				
No. of observations	15,800	15,464	29,793	61,057
No. of positive values	15,796	15,379	29,762	60,937
Mean [€/MWh]	46.68	49.81	49.99	49.09
Volatility [€/MWh]	32.82	26.23	29.16	29.50
Maximum [€/MWh]	2000.07	699.89	2436.63	2436.63
Minimum [€/MWh]	-6.84	-221.99	-151.67	-221.99
Hour-to-hour returns				
No. of returns	15,795	15,359	29,751	60,905
Mean	-0.0003	0.0015	0.0003	0.0004
Volatility	0.1945	0.2818	0.2365	0.2391
Maximum	2.1079	6.6418	6.5563	6.6418
Minimum	-4.8653	-6.3030	-6.4102	-6.4102

Table 1. Descriptive statistics for time series of spot market prices

We determine average daily price curves, representative for days in winter, summer, and intermediate seasons, as depicted in Figure 2. Following daily life, each price curve has its minimum in the morning hours, in the spot price for electricity contracts for delivery from 4 a.m. on. Spot prices rise steadily until midday in summer. Due to lack of daylight, however, a sharp increase during the morning hours is typical for the other seasons, until the according price curves reach a plateau around 9 a.m. A spike is common for delivery beginning from noon. In the afternoon, each price curve falls; so it continues throughout summer evenings. In the darker seasons, however, a substantially elevated price level is observable between 5 p.m. and 9 p.m. From 10 p.m. on, price curves for all seasons take a steady downward slope throughout the night. Our stochastic process needs to follow each of the described price movements.

For each of the three identified seasons, historical data from EPEX SPOT reveal a long-term mean, which electricity spot market prices follow. It is necessary to consider sufficiently large periods in order to eliminate short-term disturbances, and to capture long-time effects, such as economic cycles. In summary, the presented average daily price curves can be viewed as expectations for future electricity prices. To prepare for the modelling of a stochastic process, we transform the spot price series into geometrical hour-to-hour returns. Returns depict the change (slope) in a price curve, thus provide a measure for movement in electricity spot market prices from hour to hour. Geometrical returns $R(t)$ are defined as follows, with $S(t)$ being the observed spot price at hour t :

$$R(t) = \lg \frac{S(t)}{S(t-1)} \quad (1)$$

Due to definition (1), returns can be computed on positive spot prices only; negative and zero spot price values have been excluded from computation for this reason. Nevertheless, 99.8 % of initial values are preserved for evaluation, which suggests an insignificant loss. In fact, excluding non-positive spot price values is a cautionary approach we take at this moment, which remains, however, subject to further research. Additionally, for the application context of our research, the value of LS and thereby of investments into AMI would further increase with negative spot prices; thus, sensitivity would point toward a desired direction only. Table 1 also depicts descriptive statistics for the computed hour-to-hour returns. Volatilities provide an indication on spot price fluctuations, depending on the season: winter features the highest variability in returns, documenting great changes in demand or supply from hour to hour, which need to be balanced by utilities and grid operators.

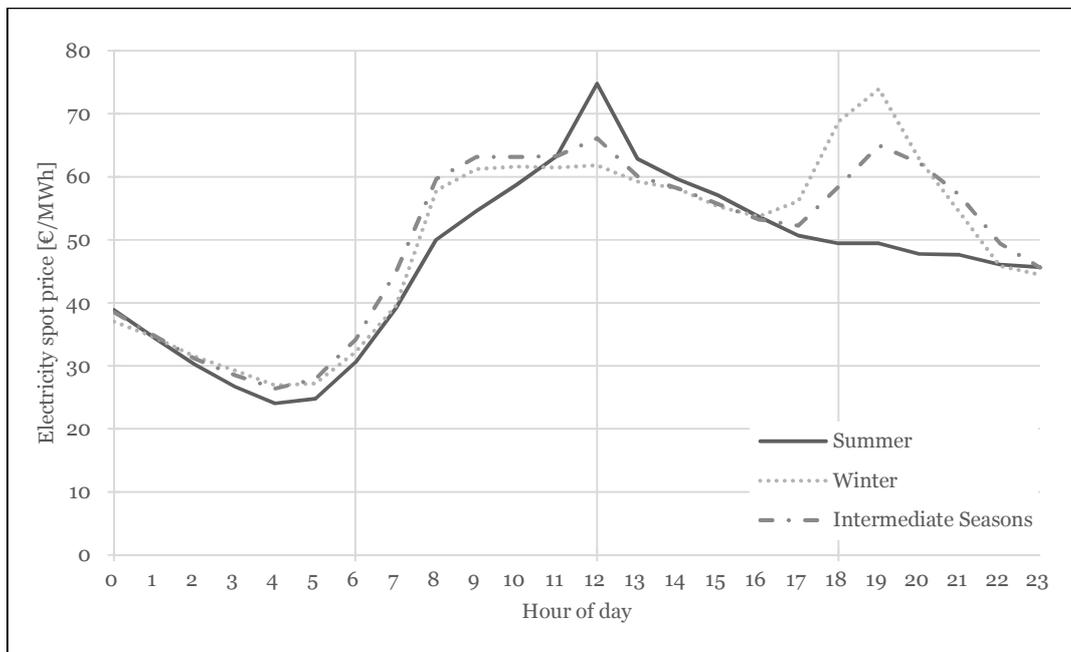


Figure 2. Historical average daily price curves

A Modified Geometric Brownian Motion Process

As we intend to provide for the valuation of LS from an intraday perspective, a discrete-time model suffices the simulation of electricity prices. For our purpose, we modify a geometric Brownian motion (GBM): a simple stochastic process which describes deterministic and uncertain changes of an underlying value S (in our case: the electricity spot price) as a function of time t . The deterministic value change in one time step (here: the expected spot price change within one hour) is described by a term $\mu S(t)$, also called drift.

With $\mu \geq 0$, the drift depicts the expected value change of the process, expressed relatively to its current value $S(t)$. Uncertain changes are described by a term $\sigma S(t)dW(t)$, with σ being the volatility of returns. The volatility controls for the influence of coincidence; and $W(t)$, a so-called Wiener process, models normally distributed returns. In summary, the GBM of $S(t)$ is described in continuous-time by:

$$dS(t) = \mu S(t)dt + \sigma S(t)dW(t) \quad (2)$$

As we intend to use a discrete-time model, we can regard a single hourly increment. Consequences are, the deterministic change in spot prices S can be set an absolute expected difference, and the returns of the Wiener process follow a standard normal distribution $N(0,1)$:

$$dt = 1, \quad dS(t) = S(t+1) - S(t), \quad dW(t) = N(0,1) \quad (3)$$

Altogether, in discrete-time, the modeled GBM is described by:

$$S(t+1) = S(t)(1 + \mu) + \sigma S(t)N(0,1) \quad (4)$$

We wish to size the process appropriately, so that it will cope with significant intraday trends in the historical spot price data. Our idea is to set the drift on every hour, in a way that the process reverts to the long-term mean until the next discrete time step ($t+1$). This means that the expected value for the electricity spot price of the next hour equals its historical average. Therefore, $\mu(t)$ is time-dependent and depicts the expected change, having regard to the long-term mean of $S(t+1)$, namely $\hat{S}(t+1)$:

$$\mu(t) = \frac{\hat{S}(t+1) - S(t)}{S(t)} \quad (5)$$

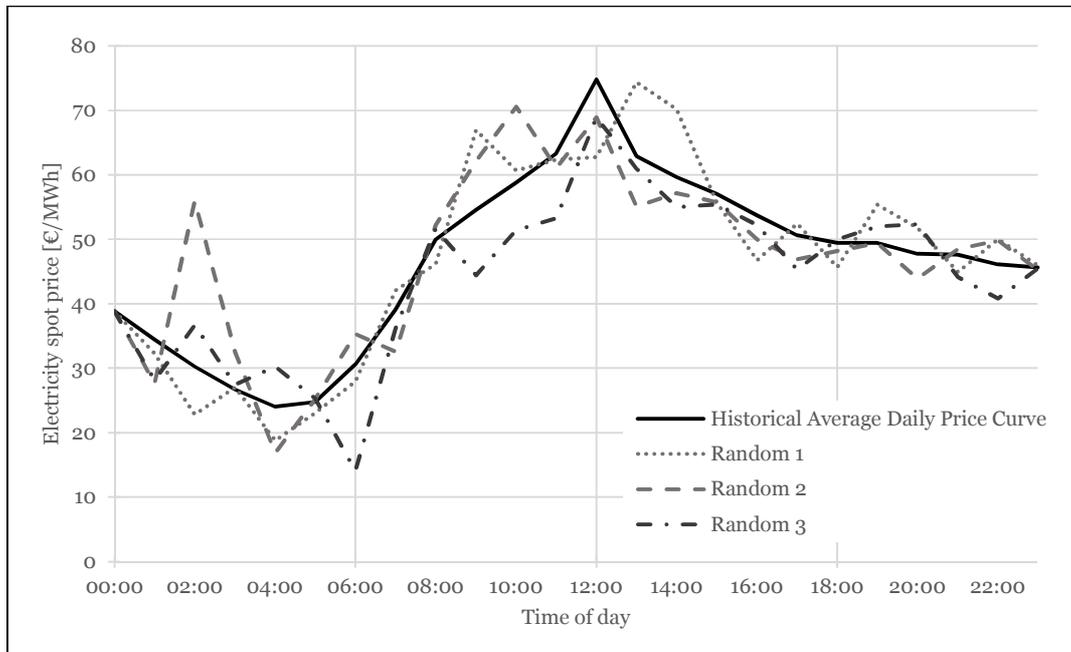


Figure 3. Summer day simulation of three random modified GBM

Uncertainty depends on a standard Wiener process, as well as on the volatility of hour-to-hour returns, which can be obtained from the historical data. Due to large differences in historical volatility, for this parameter the time of day should be regarded, too. Thus, our model considers time-dependent, averaged historical returns, as well as time-dependent historical volatilities:

$$S(t + 1) = \dot{S}(t + 1) + \dot{\sigma}(t)S(t)N(0,1) \quad (6)$$

In summary, the spot price expected for the next hour equals the long-term mean at this time of the day, complemented by a standard normally distributed source of uncertainty. At time $t + 1$, return and volatility are adjusted, and a new GBM is created. This kind of process is neither stationary (time-dependence of μ and σ) nor stochastically independent. As the result, a chain of single-period stochastic processes is tied, which constitutes a modified GBM. The resulting process chain is illustrated in Figure 3 through randomly generated numbers for a summer day, and compared with the respective historical average price curve. The diagram illustrates how simulated spot prices evolve stochastically around the long-term means. The law of large numbers implies that a simulation averaging a sufficient quantity of randomly generated modified GBM should yield the initial average price curves. Our simulation indeed confirms the expected value of the modified GBM coming close to historical data. This indicates that our process provides a realistic base for a subsequent monetary valuation of IS-enabled flexibility in electricity demand.

Conclusion, Limitations, and Future Research

In this paper, we develop a stochastic process replicating highly volatile spot price development on the electricity markets in a simple and realistic manner. Previously existing approaches could not be employed to evaluate IS-enabled flexibility for LS in the short term. We have derived our insights from spot market data covering German/Austrian market areas. Our generic model would also be applicable to other markets, like the U.S. or France, that differ in the stage of integration of renewable energy sources.

As we use a formal modelling approach, some rather technical limitations are to be mentioned: firstly, in order to simulate mean reversion, we explicitly expected the process to return to its long-term mean within one time step (one hour). However, common mean-reverting processes include a special variable for reversion speed, allowing for other speed levels which might capture price development more accurately. Secondly, describing uncertainty by a standard Wiener process is often criticized in the context of financial asset returns, because historical observations asserted heavy-tailed instead of normal distributions (Fama 1965). This circumstance does also apply to electricity prices (Weron 2008). Thirdly, by using (long-term) historical data, the sensitivity of the model to rapid changes in demand and supply is limited. Lastly, non-positive historical spot prices were neglected for mathematical reasons when computing returns, which only had a minor impact on our data set. Our stochastic process could be further developed by an extension to consider non-positive spot prices as well (Schneider 2012). For all four reasons, the modified GBM is only a simplification of reality, but proves to be useful by enabling valuation methods such as ROA. These can help assess the economic potential of flexible consumer demand and, thus, the potential of IS investments.

In the next step, our stochastic process is to be transferred into the binomial model (Cox et al. 1979), which is a common approach for discrete option valuation, and a prerequisite for ROA application: this transfer enables the risk-neutral valuation of real options describing LS scenarios. We intend to further our approach by using the stochastic process in future work: when economic potential of investments in IS for load control like AMI can be assessed, these will be able to deploy their capabilities for a sustainable energy transition.

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