Load Management in Power Grids

Towards a Decision Support System for Portfolio Operators

The increase in decentrally supplied renewable energy sources has led to growing issues with network stability. In general, both power producers and consumers can contribute to the reduction of stability problems. To this end, we propose contributions to a decision support system. On the producer side, combined heat and power plants can be used to balance the load in virtual power plants. Based on forecasts, the operators can offer a load curve. The regulation of the combined heat and power plants is able to compensate for fluctuations. On the consumer side, price signals affect consumers and intelligent appliances. The system determines appropriate price signals. In this way, a part of the energy used in homes can be shifted: "When the sun shines, the washing machine operates". Only communication from the power producer to the consumer is required, a return channel is not necessary. The practical validation of the decision support system will be conducted later in field tests.

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1 Introduction

Production structures in the power grid are constantly changing, not only in Germany. Due to legal regulations and other factors (see for example Appelrath and Chamoni 2007, p. 329), there is a trend toward decentralized supply by small plants. These suppliers include wind power plants (WPP), photovoltaic systems (PVS), and combined heat and power plants (CHP) of various constructions. Typically these PVSs, CHPs, and even some smaller WPPs are operated privately by individual households. So far, central control has not been possible on the whole. Generally, supply occurs at subsidized rates that are guaranteed over a period of years.

In the meantime, however, just the WPPs and PVSs at peak times provide sufficient electricity to endanger the stability of the power network. At the moment, there is no incentive for operators of WPPs and PVSs, or even for subsidized CHPs to interfere with the control of their plants. For WPPs and PVSs, this is also not desirable: for these types of plants, the only control option is a (partial) shutdown of production. The combination of WPPs, PVSs and CHPs to form a virtual power plant (VPP), however, unlocks the potential to include renewable energy suppliers in a meaningful way.

On the other hand, however, demand side management can be directed towards changing household energy consumption by means of price signals. In this context, the term "smart appliance" is often used. These appliances are capable of reacting automatically to price signals. In this article, we assume that no response is required of the devices, which means that we do not need to consider data security on the return channel. The price signals are transmitted unidirectionally via power line communication (PLC). For network operations, only the aggregated overall reaction, in the form of changes in consumption, can be observed.

There are various approaches to individually manage the load on the pro-

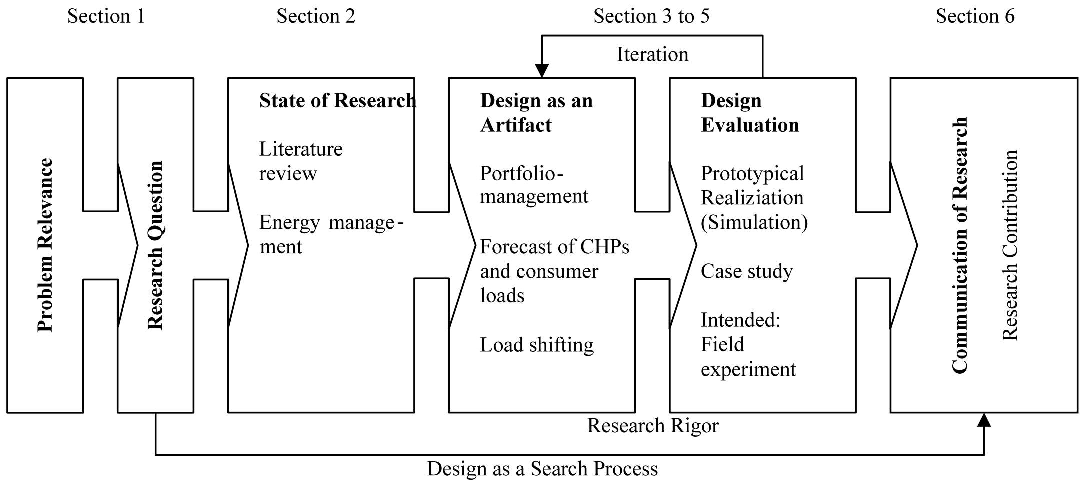

Fig. 1 Development of a decision support system with the Design Science Research approach in accord with Hevner et al. (2004, p. 83)

Table 1 Literature overview of energy management

	Producer	Transmission system operators	Energy supplier	Distribution network providers	Consumers
Appelrath and Chamoni (2007)	(✓)	(✓)	(✓)	×	(✓)
Brandt (2007)	(✓)	(✓)	(✓)	(✓)	(✓)
Tröschel and Appelrath (2009)	✓	(✓)	×	×	×
Goutard (2010)	(✓)	✓	✓	×	×
Sonnenschein et al. (2006)	(✓)	×	✓	×	✓
Eßer et al. (2007)	✓	×	✓	×	✓
Tröschel and Lünsdorf (2010)	(✓)	×	×	✓	(✓)
Molderink et al. (2010)	✓	×	×	(✓)	✓
Köpp et al. (2010)	✓	×	×	×	✓
Fluhr et al. (2010)	×	×	×	(✓)	✓
Hauttekeete et al. (2010)	×	×	×	×	✓
Stadler et al. (2009)	×	×	×	×	✓

ducer and consumer sides. We assume that in the future it will be necessary to consider the two sides simultaneously to make more efficient use of the potential of renewable energies. In this article, we are introducing an approach to a -support-system for portfolio operations that can be used to reduce short-term deviations from the long-term forecast. The remarkable thing about our approach is that the control options are offered to both producers and consumers. This leads to the following research question: "Which current and additional decision options does a portfolio operator have when considering both producers and consumers?"

To answer the research question, we used the Design Science Research approach in accord with Hevner et al. (2004, p. 83). **Figure 1** shows the approach and the further structure of the paper.

Section 2 introduces existing concepts in the area of energy management. Section 3 elaborates on the concept of the decision-support-system. Section 4 explains how the portfolio of VPPs and network operators can be optimized. Section 5 provides examples of individual simulation results and real data results. The prototypical implementation described in Sects. 4 and 5 represents an experimental design evaluation. The field test to be carried out constitutes an observational design evaluation (Hevner et al. 2004, p. 86). Sections 4 and 5 are mutually dependent, because valuable reference points for improving the model can be derived from the simulation results. Section 6 summarizes the results of the research, views them critically and provides initial recommendations for action.

2 State of Research

The state of research is summarized in **Table 1** by means of selected relevant publications, to be described in detail in the following. The table's categories are oriented around the energy flow from the producer to the consumer and the involved stakeholders. This categorization is also used in **Fig. 2** in the subsequent section. Sources whose main focus is on one of the categories carry a check mark, and those with a consideration outside of

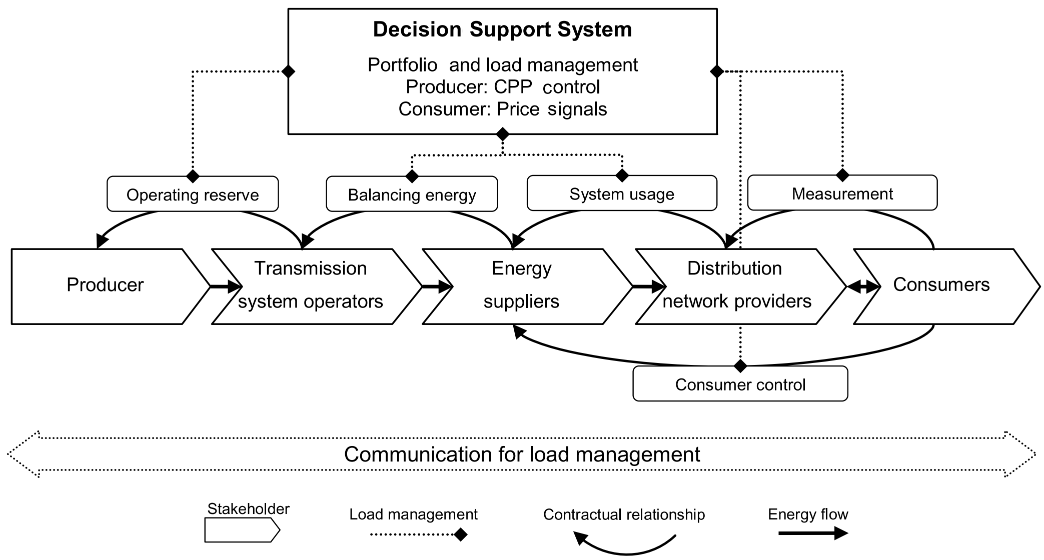

Fig. 2 Overview of the complete structure of the decision-support-system

the focus are indicated with a check in parentheses.

First, two overview articles are introduced that provide a comprehensive summary of the topic of energy management. Subsequently, relevant sources for the individual aspects are mentioned.

Appelrath and Chamoni (2007) (p. 329f.) provide a compact, concise introduction to the topic and also identify the "politically desirable distribution of producers such as wind power plants, solar cells, biomass systems, fuel cells, and combined heat and power (CHP) plants" as the strongest drivers for IT integration into energy supply. They indicate a strong concentration on research in the technical sector. Despite a greatly increasing number of publications in the last few years, the literature review done for this article shows that this trend is continuing, even after five years: A large proportion of publications stem from engineering scientists, and many are published for IEEE conferences and in IEEE journals.

Brand (2007, p. 380f) provides a good overview of the numerous projects and (some internet) sources for researching IT systems and new IT concepts in the energy sector. Many of the projects are not yet complete. Brand points out that "Changes [require] [. . .] new IT concepts and systems" (p. 380).

Tröschel and Appelrath (2009) (pp. 141–143) describe a VPP approach as being part of decentralized energy management. To counteract an uncoordinated network supply, they choose a multi-agent-based approach for coordinating the distributed production plants that are bundled into the VPP. Tröschel and Appelrath consider the correction of deviations from the forecast to be an important task of energy management when including distributed producers.

As a result of the increasing amount of OR energy generated by renewable energy producers, Goutard (2010) observes the need for changes to energy management systems that have been in use for decades. He describes the special characteristics of renewable energy producers and their effect on the basic functions of today's energy management systems. The specific difficulty with forecasting wind energy leads to increased complexity with regard to managing energy flow and ensuring network stability through reliability coordinators. Fundamental to this is the availability of real-time data and if this is not possible, at the least of a good estimation of the current amount being produced. Forecasting regenerative energies is seen as one of the key factors of secure network operation. Energy management needs to anticipate multiple points of time and should also consider the operation of renewable energy producers such as wind power plants with artificially reduced performance. According to Goutard, the system for operations should include an expanded visualization and a training simulation with special scenarios for renewable energies.

Sonnenschein et al. (2006) describe an agent-based approach to simulating real-time pricing of consumption. The integration of many non-controllable producers as locally as possible is indicated as a motivating challenge. Sonnenschein et al. consider data communication to be the foundation for the management of the energy network and especially for the wide use of load management in homes and offices.

Eßer et al. (2007) point out the increased complexity within the energy market and a change from static consumer-oriented approaches to a dynamic market-oriented approach. Based on the SESAM project, a distributed marketplace for energy trade between energy suppliers, small consumers and CHP operators is viewed as a possible future scenario. In addition to technical aspects, ecological and legal points must be taken into account. Eßer et al. (2007) simulate such a market and its effect on private customers and CHPs.

Tröschel and Lünsdorf (2010) examined various strategies for energy management in the distribution network. They recommend a combination of expanded CHP control and load management by the consumer.

Molderink et al. (2010, p. 1) describe a three-step approach to energy management of homes with a focus on power supply situations to be expected in future: The first step includes predicting the power supply by the CHP based on an individual heat-demand forecast that is based on artificial neural networks. In the second step, the combined CHPs in the VPP are installed with hot water storage tanks. In the third step, the electric consumers are locally regulated to balance the remaining difference between production and use. Molderink et al. test the process with both a case study with simulation and a field test. The quality of the power supply prediction is identified as the critical factor.

Köpp et al. (2010) examine load management from both the consumer and the producer sides by means of simulation. To influence consumption on the consumer side, variable electricity prices are proposed in connection with smart appliances. Various price-optimizing control strategies for household devices are studied. On the producer side, central control of CHPs based on predicted heat requirements is simulated. Köpp et al. argue that a combination of the two approaches should be used.

Fluhr et al. (2010) discuss the integration of electric vehicles into the power network. They postulate that electric vehicles are parked 90 % of the time, and more than 25 % of that time they are parked at the user's home, offering a large potential for load balancing. Based on a stochastic model of time related and local availability of electric vehicles as well as data from a survey of 25,000 households, they performed a simulation. Intelligent load control is described as absolutely essential, as otherwise the network would be burdened with intense peaks. Overall, the concept of V2G (Vehicle to Grid) is acknowledged to show high potential.

Hauttekeete et al. (2010) believe that the consumer has not been sufficiently taken into account within the smart grid concept. They introduce several ideas and studies on consumer-side energy management and criticize the non-specific role definition of (private) consumers. They further discuss weaknesses in the current empirical studies of the consumer side. They suggest examining user acceptance based on TAM, taking special care to use realistic scenarios and to select households that represent the overall population.

Stadler et al. (2009) study an approach which aims at influencing consumers through the direct control of refrigerators. This is supposed to reduce the need to switch off renewable energy suppliers and also the need for expensive storage capacity as a result of erratic production. An aggregated model is derived from the model of individual appliances and this model is examined through simulation. Stadler et al. consider the lacking opportunity to observe the uninfluenced load profile of controlled devices an important problem. This makes global control difficult.

The literature overview includes the large field of virtual power plants on the producer side. Even though there are different definitions, virtual, centrally controllable energy producers are often understood to include WPPs, PVSs and CHPs (as a buffer). CHPs are able to partially compensate for forecasted changes to WPPs and PVSs temporarily by means of a hot water storage tank. This approach is also used in this article.

The possibility of using various methods to shift the load to the consumer side is often considered. In summary, it can be said that price incentives often affect household load (among other things). This article also uses price signals for load balancing. To what extent the proposed approaches can be established, especially on the consumer side, is the subject of fierce debate.

Up until now there has been very little research (all of which has been published more recently) that explicitly deals with the integration of power producers and consumers. As an alternative to the concept introduced here, we mainly refer to the approach from Tröschel and Lünsdorf (2010). They do not introduce a VPP and use individual controllers instead. The objective is, among other things, to smooth out and thus shift the load. However, in this article, we are not focusing on load smoothing or shifting of CHPs, but on balancing load by means of the CHP. The main difference to the study by Tröschel and Lünsdorf, though, lies in the fact that the study authors focus on a control signal for groups of household appliances in contrast to this article which uses prices signals that can be evaluated for each household appliance independently.

Overall, this short literature review shows that the investigated sector is being actively and diversely studied by a wide variety of scientists and practitioners. However, integrative approaches have only been considered infrequently to date. Both the fundamental significance of the area of research and the relevance of the proposed approach derive from these facts.

3 Decision Support System for Energy Management

Figure 2 shows the structure of the proposed decision support system. This paper will provide first partial approaches to a possible future implementation. The schematic illustration summarizes the relationships between the individual stakeholders and their contractual links. The paper focuses mainly on virtual power plants on the producer side. These plants use CHPs to compensate for short-term fluctuations in WPPs and PVSs. This reduces the need for balancing energy, which is generally expensive. On the consumer side, the goal is to further adapt the household load to production by means of price incentives.

To implement load management, the individual stakeholders each need information about the neighboring stakeholders. Concrete improvements, such as preventing imbalances between production and consumption, can be achieved by specifically influencing energy production (VPP control), balancing energy, measurement and analysis of consumption, and consumer control. The proposed decision support system helps users select a suitable method for managing loads.

Figure 3 shows the control options and the interlocking of the participants in the power market, based on various time frames that can be considered during planning. Power producers and consumers are connected via the portfolio. The portfolio takes on the role of today's energy suppliers. Different producers feed into the portfolio and different consumers are supplied from the portfolio. As is usual for the energy branch, the portfolio is considered to be a "copper plate", which means that it does not (yet) matter where the various in feeds and extractions. However, it is important to have a balanced portfolio for each point in time. If necessary, this must be achieved with balancing energy.

A portfolio operator usually strives to balance the portfolio with long-term contracts. In addition, the operator can make use of the conventional market (i.e., conventional energy markets, such as European Energy Exchange (EEX)). In the future, shorter-term fluctuations (relevant planning horizon is a segment of only a few days) can be balanced on the smart market. The smart market allows

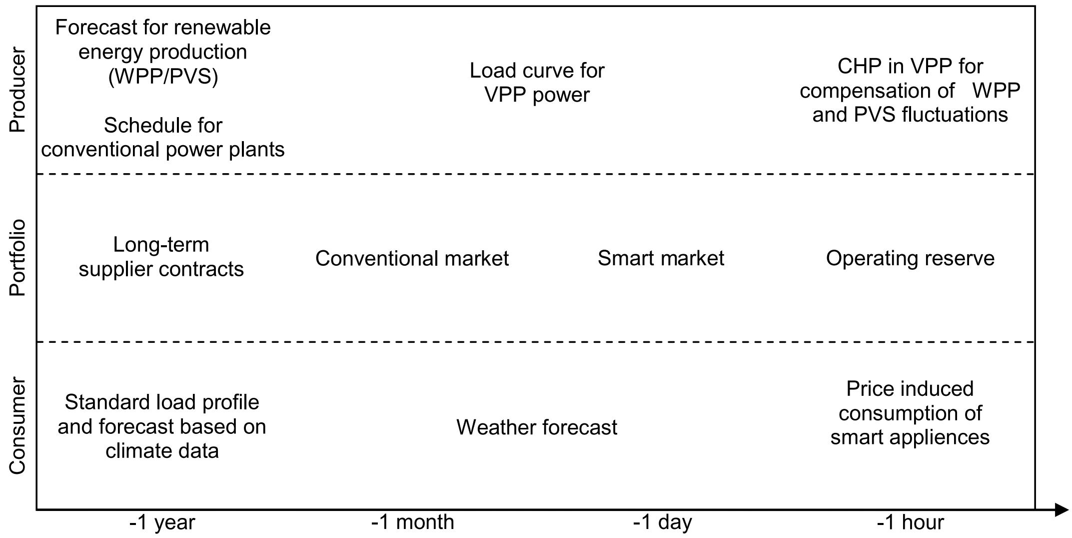

Fig. 3 Control options for the energy management system

energy trading in finer granularities than the EFX does. Non-standardized products can also be offered. Here we point to the cornerstone paper "*Smart Grid*" and "*Smart Market*" from the German Federal Network Agency (Bundesnetzagentur 2011).

So far, portfolio operators had to compensate for short-term fluctuations by using balancing energy. However, when CHPs are used in a VPP, these types of fluctuations on the producer side can be considerably reduced. In this paper the following configuration is selected for a VPP: A VPP operator is obliged to provide the portfolio operator with a defined load curve (VPP power in **Fig. 3**). If the VPP operator determines that the agreed load curve cannot be met, the operator attempts to compensate for the difference by using CHPs.

On the consumer side, as part of the proposed decision support system, there is also the option to use price incentives for shifting the load. The decision support system does not include the seconds' range. Wedde et al. (2007, p. 365) describe such an approach.

In the past, control of the portfolio was mainly realized long-term (left in **Fig. 3**). With an increasing proportion of renewable energies, the planning horizon is shifting towards the short-term sector in portfolio control. The time frames examined require more flexible control options than those used today. However, flexibility is increased by considering producers and consumers simultaneously. Ultimately, the human decision maker is responsible for selecting the proposed control options and, more importantly, for combining them.

Different approaches for the producer and consumer sides are required to implement load shifting and thus generation of a decision support system. Overall, it seems that very similar (and established) processes for conventional portfolio optimization can be used on both consumer and producer sides. This lowers the hurdle to use the proposed approach. Every energy supplier already has the required software and does not need to invest further (or only very slightly) for the optimization tasks.

4 Portfolio Balancing that Takes Both Producers and Consumers into Account

The conventional portfolio (see **Fig. 3**) initially remains unchanged: As usual, first the long-term supplier contracts are used for optimization. Next, possible short-term supply comes in addition from the conventional market (such as EEX). Also supply from the smart market may be utilized, as needed. The smart market, however, does not fundamentally differ in contractual arrangements from the conventional market. The decisive difference is the additional flexibility: users can deal in much smaller amounts, and these are of a more flexible structure than available in the conventional market. However, this does not negatively affect portfolio optimization.

In conventional portfolio optimization, after its execution a residual amount would be left on the contracts, which would have to be compensated for with balancing energy. In this article, we attempt to minimize these residual amounts through price-induced load shifting in households. Thus the conventional portfolio optimization process can remain the same. In order to calculate a compensative price signal, only the residual amounts are passed on to the artificial neural networks (ANN).

Here we need to be aware that a load shifting induced by prices is not sufficient to eliminate the residual amounts in every case. Balancing energy will continue to be necessary. However, load shifting will reduce the amount of energy required.

The VPP operator's portfolio is important as the second component. VPP operators are obligated to supply a defined load curve. This load curve is determined (see **Fig. 3**) by means of the predicted production of PVSs, WPPs, and CHPs. This forecast is dominated by weather data. VPP operators only need to take action when unpredicted weather changes result in a fluctuation in production. If fluctuations occur, VPP operators must try to maintain the load curve by controlling the CHP. Otherwise a conventional penalty will be awarded. This problem is also one of portfolio optimization, which can be approached using conventional portfolio optimization: the changed (forecasted) PVS and WPP production is taken as the agreed "contract to supply". The differing amount from the registered load curve is produced by means of the CHP.

When forecasts change, the amount of power to be supplied by the CHP deviates from the original (unchanged) CHP production. Here the VPP operator takes action by modifying the CHP control. While controlling the CHP, they must be aware that it is heat driven. In this context, the generated power can be regarded as a waste product; however, it directly depends on the heat requirements of the respective building. Action taken in CHP control to balance out any short-term fluctuations in renewable energies has to take into account the (predicted) heat requirements. If this is not considered, too little heat is produced. This results in a loss of comfort for the CHP user. Alternatively, too much heat is produced and the CHP has to be turned off when it reaches the maximum storage temperature. This overproduction of heat is also a waste. In general, a good CHP heat requirement forecast is an important basis for VPP control. Köpp et al. (2010) provide examples for these types of forecasts.

On the consumer side, smart appliances provide the possibility to shift loads. These appliances receive price signals via PLC and can react to them in a useful way. It is recommendable to activate appliances during the most inexpensive time period within an operation time frame determined by the user. This is just an example. The user can also choose other operating parameters, as needed. In this approach, no bidirectional communication (i.e., no return channel) is required of the appliances. The price signal is broadcasted to all (or to select groups).

One challenge when designing the proposed decision support system is the fact that precise appliance behaviors are not yet completely known. It is thus important to develop a process that can robustly process incoming real data.

To that end, a simulation is used to examine various types of appliances and their reaction to price signals. A detailed description of the simulation is provided in Sect. 5. Various strategies can be used. However, all of the strategies have one thing in common: smart appliances aim at utilizing the lowest possible electricity price during a given operating interval. Therefore the connection that results is "price signal → load change". This can be illustrated by means of a hot water heater with large storage capacity. These large boilers are especially suitable for use in passive houses without emissions. Due to its good insulation, the warm water storage unit can cover a household's hot water needs for an entire day when fully heated. For that reason, from a user perspective, it is irrelevant at what point over the course of a day the boiler is heated as long as it is heated every day. A smart boiler would heat up during the cheapest time of the day. If the most inexpensive time of day is too short to fully heat the boiler, the heating phase is split and completed in the regarding part of the next-day. This type of appliance was simulated and the reaction to various price signals was observed.

However, for the field test, the correlation between "desired load changes → inducing price signal" is required. That means that a functional representation is sought that provides the appropriate price signal for a desired load curve. Since the individual devices of each household are not known in the field test, an approach that works with the observable data aggregate must be applied. Therefore an artificial neural network (ANN) is used, as described by Haykin (2009, p. 152ff.), which learns the correlation between load change and price signal. As a universal approximator (Haykin 2009, p. 197f.), the ANN is able to bring interval functions in line as precisely as required. ANNs are also widespread in the energy industry, as described by Köpp et al. (2010), Nwulu and Fahrioglu (2011), von Mettenheim and Breitner (2010). Even though the studies mentioned here do not explicitly deal with determining prices signals, in the current context it makes sense to use ANN since it is also able to learn the step function to any level of precision.

Fast Approximation with Universal Neural Networks (FAUN) is used for neurosimulation (Breitner 2003, p. 165; Köpp et al. 2010; von Mettenheim and Breitner 2010). ANN is a 3-layer perceptron with an inner neuron. As is most often the case, a sigmoid function is used as the activation function; here we used the hyperbolic tangent. The objective of optimization is to minimize the square difference of network output and desired value. Other error functions that more strongly emphasize the fundamental technical correlation can be used, but these were not considered any further, in order to be better able to interpret the results. The inputs are:

- 12 hours of historical differential load curve,
- 18 hours of historical electricity price,
- target differential load curve for the upcoming hours.

Network output is the electricity price for the upcoming time period. The given past values are determined using a gradual neural regression so that the model remains as economical as possible. Training is done by means of a back propagation algorithm (Haykin 2009, p. 159f.). This is a sequential quadratic programming (SQP) algorithm with Broyden-Fletcher-Goldfarb-Shanno (BFGS) quasi-Newton updates (von Mettenheim and Breitner 2010). The SQP mostly works without any user parameters. It is particularly significant that the explicit specification of a learning rate or a term of momentum, both of which is usually required for neurosimulation, becomes unnecessary, because the optimization process automatically determines the direction of descent to minimize errors. The FAUN neurosimulator uses the SQP process to reach convergence much more quickly than the usual neurosimulators with gradient descent (Breitner 2003, p. 165f.).

Cross validation is applied to prevent overtraining. A concrete configuration, for example, results from 3540 training data sets and 1062 validation data sets. During training, the error is observed in the validation data. While training errors continue to occur, the validation error increases again after some time. If it increases twice, it assumes that overtraining has started and the network is released.

Every network trained in this manner undergoes quality checks. To do this, the validation error is divided by the training error. If this quotient exceeds the acceptable quality criterion, the network is discarded and a new training with randomly initialized weights is started. With FAUN it is possible to adjust the validation quality depending on the problem. For this study, the value 1.5 is used. This value has proven successful in many similar problems.

One frequent problem with ANN is that it can get stuck in bad local minimums. To avoid this, 1000 networks are each trained with different weight initializations. The ANNs with the fewest errors are used for the model. To prevent occasional oscillations, the five best networks can be consolidated into an expert round topology, for example. The output signal is the unweighted arithmetic mean of the individual networks. In addition, with FAUN the total curve

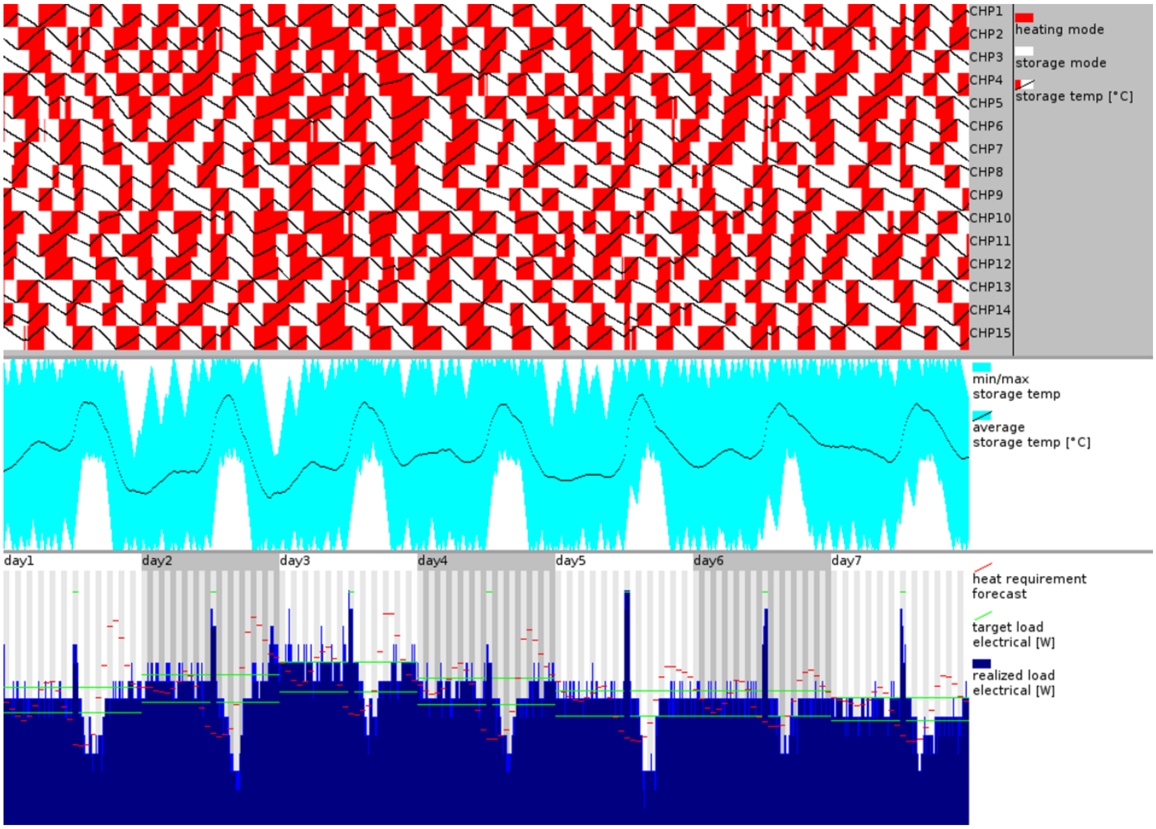

Fig. 4 Screenshot of the prototype: Generation of an (almost) continuous load curve (*bottom*) by specifically activating individual CHPs (*top*). The *center curve* reflects the storage tank temperature of the CHP

of the ANN can be minimized, resulting in a smoother function (Breitner 2003, pp. 130).

The generated network is first validated by simulating again: The price signal that results for a given load change is entered into the simulation. The load change determined by the simulation is then compared with the given load change.

5 Prototypical Implementation and a Case Study

Because the introduced approach essentially prepares the ground for later trials in the field test, we developed a software prototype. The prototype examines two important aspects of the proposed energy management system, the load shifting on the consumer side and the control options provided by the CHP.

Figure 4 shows the part of the prototype that can be used to control the CHP. The simulated CHPs are oriented towards the technical data of the well-known Dachs series from Senertec, with a hot water tank capacity of 750 liters. It is initialized with a random annual running time of 3000 to 5000 hours. In the lower part of the figure, a band becomes visible which comprises the CHP power output. The simulation confirms that just a few (in this case 15) CHPs are sufficient to keep the power output within a narrowly defined band. A corridor (as opposed to an individual target value) is selected because a precise achievement of a target value does not seem possible. Striving to precisely maintain an individual target value would lead to flutter switching, especially with a lower number of CHPs.

Figure 4 is an example application that was selected for graphic illustration. In later applications, it will not be important to maintain a constant band. It is of greater importance to make corrections in case of fluctuating PVSs and WPPs. The target performance results from the difference between the agreed load curve and the current forecast from PVSs and WPPs.

In **Fig. 4**, however, it is apparent that problems can arise. One example is the sharp decline of the power output in the second half of the first day: numerous CHPs must be shut down due to the storage tank temperature being too high. This prevents operation outside of the specifications. The opposite phenomenon can be seen in the second half of the third day: due to an insufficient storage tank temperature, some CHPs are forced into operation. Thus more power output is produced than required. This prevents a loss of convenience for the CHP operators.

Figure 5 uses the hot water heater described in Sect. 4 to provide an example of how price signals can contribute to load shifting in households. The upper part of the figure shows an initial price curve. The respective hourly price for the time frame from 0:00 to 23:59 is given. The benchmark of 20 ct/kWh becomes visible by means of the division between the upper and lower subsectors. Prices are allowed to fluctuate around this mean value in a band of 15 ct/kWh to 25 ct/kWh. In this example we assume that prices are known 24 hours in advance. The method described here can also be used for shorter preview intervals with good results. It is appropriate to look at different preview intervals: longer intervals give the consumer better operating prices; shorter intervals increase the

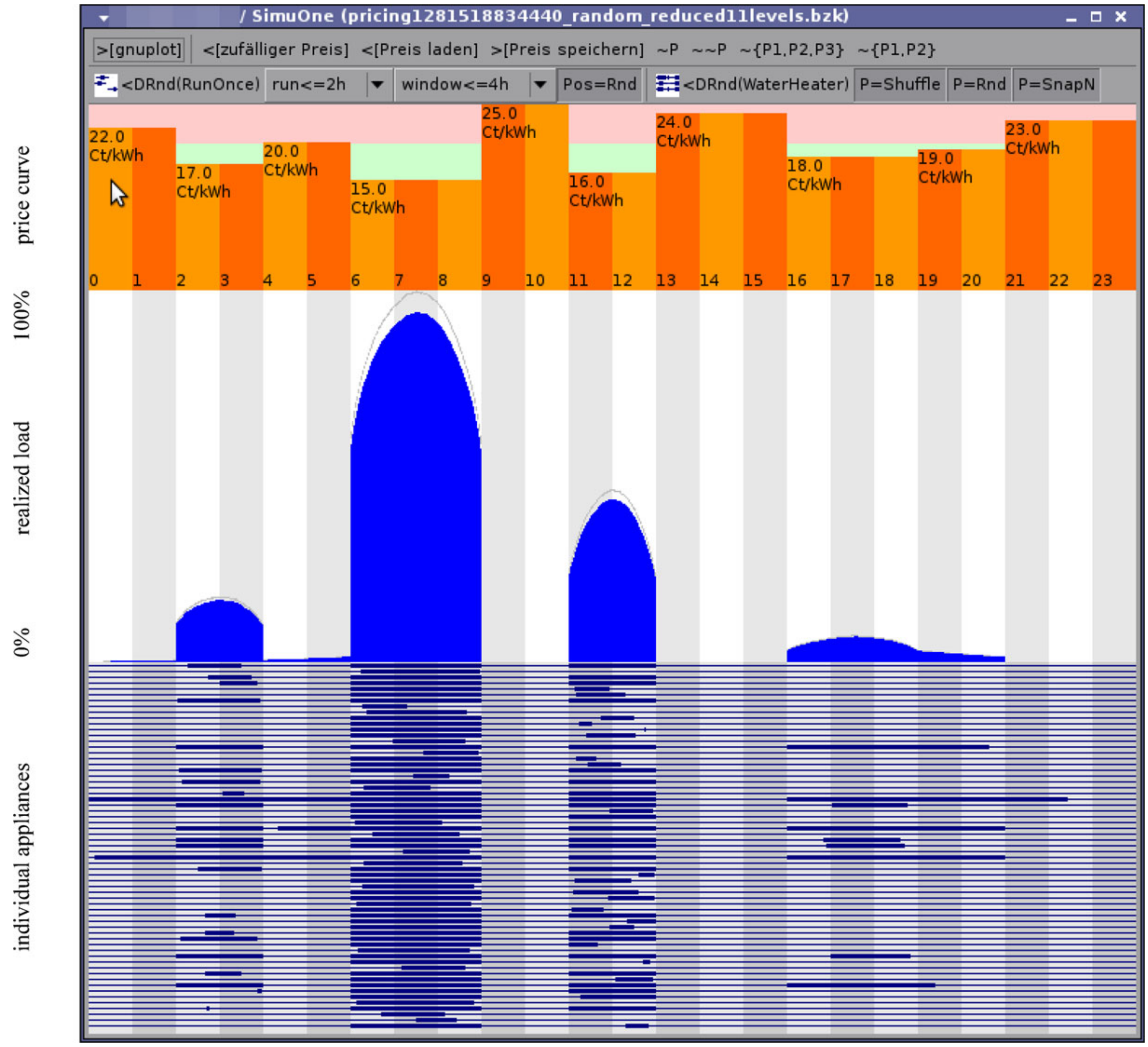

Fig. 5 Screenshot of the prototype with simulated hot water heaters with large capacities: Price signals (*top*) lead to a changed load curve (*center*) and execution times for individual appliances (*bottom*)

flexibility of the decision support system. An acceptable compromise between the two must be found.

For better illustration, the unaffected base load is not shown in the middle part of **Fig. 5**. Instead only the realized load curve of the smart appliances is given. This realized load curve ranges from 0 % (none of the appliances is running) to 100 % (all of the appliances in the aggregate are in operation) of the total appliance output. This simulation includes 10000 hot water heaters, the daily operating time of which is determined randomly based on technical data from commercially available hot water heaters. The lower part of **Fig. 5** also shows the operating time of the individual devices, to envision how these are distributed. In the center and lower parts, it is obvious that the load is shifted to the cheaper times and that the most expensive times are omitted. Appliances that must operate over a longer period try to avoid the most expensive times and instead use the relatively inexpensive times (for example, hours 19 and 20).

Figure 5 shows an example of the simulated behavior of hot water heaters. The behavior of smart household appliances (such as washing machines, dryers, and dishwashers) was also simulated with good results. The following strategy was assumed for appliances of this type: Within one of the operating times determined by the user, the appliances are activated once without interruption when the overall least expensive price is available. For operating times within the previewed time period, in this way, from a consumer point of view the price-optimized behavior is achieved.

During development of the prototype, we laid great emphasis on adaptability and expandability. At present, we still need to finalize which savings strategies should be tested with appliances. New appliance types and new savings strategies can be implemented quickly due to the modular architecture. The prototype also enables quick integration of new data. That means that retraining the ANN is sufficient for adding current knowledge to the calculation logic.

Five hundred homes in North Rhine Palatinate are scheduled for the field test. Some of these households will be equipped with smart appliances. The appliances include washing machines, refrigerators, and "smart" electrical outlets. These outlets switch the connected consumer on when the price drops below the threshold set by the user. In this way, suitable appliances in these households can be used in the field tests. Heat pumps are another appliance available for the field trial. Consumer data will be provided by the energy supplier every hour, which means that the effect of the price signals can be checked directly. A learning phase of four weeks will enable us to experiment with price signals and calibrate the system. Then the price signals will be actively used to shift loads. New data can regularly be integrated into the model. Post-training of the ANN is possible within a span of a few minutes. The field test is a practical evaluation of the proposed design and will most likely run over a period of a year.

6 Limits, Summary, and Outlook

The proposed approach to a decision support system for energy management is based on both producers and consumers. We first introduce controls for a VPP on the energy-producer side. These controls enable VPP operators to maintain an agreed load curve within the framework of technical limits by specifically switching CHPs on and off. The process improves the integration of WPPs and PVSs. The goal is to reduce both the need for additional balancing energy and the need to make power plant output available to produce balancing energy.

To be able to better adapt to the actual power production, we propose sending price signals. Smart energy consumers evaluate the price signals and start operating when the electricity price is inexpensive. An individual return channel for each appliance is not necessary, because the behavior of the appliance aggregate is simulated. We have demonstrated that a meaningful, albeit limited load shift is possible, even if assumptions concerning actual appliance strategies are stretched.

The two approaches have in common that there is no attempt to smooth out the load curve. It is far more important to reproduce the load curve as precisely as possible. Thus the approach is much closer to reality with its increasing proportion of volatile renewable energy producers. The algorithms developed are implemented with the help of a leading German software supplier in the process control for energy supplier sector and are currently being tested in the field.

The prototype shows that the proposed approaches contribute to solving stability problems which are already occurring frequently. In comparison to other concepts, only few small changes to the existing technical infrastructure are required. Production plants generally already possess remote maintenance access over the internet. Controls can be implemented by these means. On the consumer side, as part of introducing smart metering, the required technical prerequisites are already complete so that household appliances can be controlled via PLC.

It should be kept in mind, however, that the technical measures introduced in this paper represent merely one component of many in future energy strategies. Even more important are the legal framework conditions, as well as the acceptance of smart household appliances by the public. As to current electricity prices, for example, it is currently unsettled whether completely flexible tariffs, which are beneficial to a price-sensitive load curve, will be approved of by legislation. Another open question is to what extent these tariffs will be accepted by consumers. This requires an empirical study, which, however, would imply considerable additional effort and expense, because each tariff approach would need to be studied separately. There is also a demand for incentives to encourage customers to switch to a dynamically priced electricity rate.

Mainly from the consumer side, there are also additional ideas: Much more precise load shifting is possible through direct control on the level of individual households or even individual appliances. However, the intervention options for users and thus the expected levels of acceptance are limited. Global control brings along the challenges of an enormous optimization issue. To avoid this scaling problem, approaches have been proposed with multiple hierarchy levels for optimization, or even agent-based concepts. Bidirectional communication is usually required, which necessitates a more complex infrastructure.

One limitation is that the prototype presented here does not depict a complete energy management system. It does offer new important building blocks for a comprehensive system. Another limitation of this approach is the fact that it does not consider distributed feed-in. However, it is already apparent that decentralized feed-in is increasing in importance. In the future, on the producer

Abstract

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Load Management in Power Grids

Towards a Decision Support System for Portfolio Operators

Decentralized renewable energy sources become more and more common. This leads to stability problems in power grids. Conventional energy sources are easy to control. In contrast, wind and solar power are much more difficult to forecast. Forecasts are only possible short term and are more imprecise. Producers and consumers of energy can try to help reducing stability problems. Contributions towards a decision support system are proposed and recommend how to alter the behavior of producers and consumers. On the producer side centrally controlled heat and power plants are able to shift load in a virtual power plant. The plant operator offers a load curve based on forecasts. The centrally controlled heat and power plants help to mitigate the effect of revised forecasts. An incentive based control on the consumer side is also proposed. Smart appliances react to pricing information. They alter their execution window towards the cheapest time slot, if possible. The exact behavior of appliances in the expected field experiment is still partially unknown. It is necessary to simulate the behavior of these appliances and to train an artificial neural network. The artificial neural network allows computing the pricing signal leading to a desired load shift.

Keywords: Load shifting, Virtual power plant, Management of complex energy systems, Artificial neural networks, Simulation, Smart devices

side this should be accomplished via regionally adapted control of CHPs, and on the consumer side through prices that differ according to both time and region. As proposed in other studies, a hierarchical structure might be useful here, but different forms of hierarchies are possible and practicality would have to be looked at.

As part of this study, an option for control on both the producer and consumer sides was considered. This provides additional decision options for portfolio operators. If a divergence between the predicted and actual production or load emerges, operators can choose the best control option according to criteria that they defined (ecological, economical, or a combination of the two) and depending on the planning horizon. The combined approach offers the potential for short-term intervention with a decreased need for balancing energy. The authors are aware that the proposed options are not exhaustive. Other promising concepts such as vehicle to grid (V2G) have so far not been considered. The proposed prototypes will be integrated into an existing energy management system as part of a field test, thus considerably increasing the control options.

As a contribution to the discussion within the scientific community started by Hevner et al. (2004), it is argued that the use of decision support systems with simultaneous, intelligent control of electricity consumers and electricity producers can improve the integration of renewable energies. However, only an empirical study can determine whether the results of the simulation reflect reality precisely and sufficiently. Notwithstanding the above, we must be aware that the combined consideration of producers and consumers has only been discussed sporadically in the literature.

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