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Content

Introduction

The energy supply and demand transition with its goals for the conversion of the energy system to climate-friendly and sustainable energy resources leads to drastic changes in today's energy systems (heat, mobility, and electricity). The associated digital transformation in the energy sector offers a wide research spectrum with planning and analysis of energy supply structures, system-technical implementation of accompanying ICT infrastructures and modeling, simulation, transformation, and optimization of current and future energy systems. Significant economic benefits can be generated expanding historically grown power grid infrastructures into ICT-managed intelligent networks that use the flexibility of loads and generators. Energy Informatics and with it also Business Informatics deals with the interaction of distributed, heterogeneous and differently interested stakeholders in the energy sector with the help of ICT components, sensors, and actuators and on electronic markets.

The community workshop "Energy Informatics and Electro Mobility ICT" focused the software level and particularly included extraction, generation, storage and consumption systems (heat, mobility and electricity). E.g., tools and methods were discussed to achieve a system-inherent optimization of the energy supply in terms of distribution network operation or local or regional energy management. Furthermore, data models and algorithms for the organization, coordination and interaction of stakeholders including data and privacy protection were discussed. Not only technological aspects play an important role in this transformation process, but also the involvement of consumers and prosumers. Thus, attention was not only on the development, evaluation, and application of new technologies, but also on the human-machine interaction. Relevant concepts and components in energy supply also require suitable incentives and marketplaces for investors, producers, consumers, and prosumers as well as adjustments of regulatory frameworks to fully exploit the potentials of smart nano, micro and macro grids. E.g., technology acceptance or consumer and prosumer usage of relevant components form critical success factors. Challenges discussed also addressed the energy supply for heat, mobility, and electricity in an integrated manner including electro mobility ICT. Accepted papers cover topics and research questions like

- ICT-based coordination of decentralized electricity producers and consumers, e.g., "supply and demand matching" and "demand side management",
- (multi-)agent systems, autonomous and autarkic systems and self-organization processes,
- cross-sector energy approaches in ICT-based energy system optimization,
- software and system architectures,
- decision support systems as well as forecasting and scenario analysis tools,

- ICT in smart micro and grids including interfaces and data and privacy protection,
- cost-efficiency evaluations of energy systems as well as economic and sustainability aspects (heat, mobility, and electricity),
- concepts and ICT support of central and decentralized market mechanisms as well as regulation,
- business models and ICT services,
- technology acceptance and behavioral aspects of market participants w.r.t. components, incentive systems, tariff models and price mechanisms (supply and demand for heat, mobility, and electricity),
- ICT for electro mobility and
- industrial load management.

The community workshop “Energy Informatics and Electro Mobility ICT” in March 2021 was part of a cycle with the renowned annual Energy Informatics conferences “ACM e-Energy” (June) and “DACH+ Conference on Energy Informatics” (October). The focus chosen was on Business Informatics and digital transformation to extend the Energy Informatics community focus of the two above mentioned conferences, which traditionally are both technically oriented. 13 papers were submitted at the end of 2020, 9 papers were accepted and presented in March 2021 and 8 papers are now part of this proceedings.

Oldenburg, May 2020, the editors Michael H. Breitner, Sebastian Lehnhoff, Astrid Nieße, Philipp Staudt, Christof Weinhardt, and Oliver Werth

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Online Operation and Profitability Evaluation for a Multi-Tasking Community Energy Storage with Prioritized Services

Abstract. We introduce a strategy to allocate a community energy storages' capacity amongst several tasks with different priorities. We consider the tasks of increasing self-consumption of solar generation, ancillary services and arbitrage trading. The maximization of self-consumption from PV rooftop generation is assumed to be a preferred task due to consumers' preferences and regulatory considerations. Our case study shows that while the single use-case of self-consumption is unprofitable during the storage lifetime, a multi-tasking deployment leads to a positive net present value. The proposed strategy largely succeeds in maximizing the prioritized task of self-consumption, only causing small interferences with the scheduling of the other tasks due to uncertainty. We further find that arbitrage trading on the wholesale markets decreases net present value due to disproportionate effects on battery degradation.

Keywords: *community energy storage, multi-tasking storage, multi-purpose storage, prioritized services*

1 Introduction

The transition towards a decarbonized energy supply is driven by investment in distributed, intermittent energy resources (DERs) such as photovoltaic systems (PV) or wind turbines. A challenge that comes with this transition is the increasing volatility of the electricity supply that needs to match demand exactly at all times to ensure system stability. The expansion of intermittent DERs must therefore be accompanied by extensive demand and generation flexibility measures, especially in the low and medium voltage distribution grids that most DERs are connected to. In distribution grids, Battery Energy Storage Systems (BESSs) can help to resolve congestion and shift excess generation to times with more demand. As with the expansion of PV, the driving impulse for the increasing adoption of BESSs comes from local residents. In the course of decreasing storage system costs and subsidies for the joint purchase of a PV plant and BESS, an increasing installation of residential BESSs can be observed in Germany [1, 2]. Due to current regulation, increasing self-consumption is the only feasible option for residential users to profit from a BESS. This limits the economic potential of BESSs as the utilization is restricted to the cyclic nature of solar generation. However, research suggests that the economic viability of storage systems can be enhanced substantially by combining several tasks and therefore exploit idle capacities [3, 4]. Possible applications for BESSs range from trading electricity on the wholesale spot markets to providing ancillary services such as frequency containment reserves (FCR) and frequency restoration reserves (aFRR) [4]. The latter applications have the advantage that, in addition to increasing profitability, they are also beneficial to grid stability. However, there might be other incentives than economic profitability alone. Especially in a residential setting, research suggests that storage owners value a higher self-sufficiency with "green" electricity from their own solar generation [5]. Promoting self-consumption from rooftop PV generation may also be a desirable goal for the regulator as it can lead to reduced peak feed-in in network sections with generation surplus. In this contribution, we therefore investigate the multi-tasking deployment of a residential storage system that prioritizes self-consumption and answer the following research questions:

- How can a storage management allocate the available capacities of a multi-tasking community energy storage to applications with different priorities?
- How profitable is the multi-tasking deployment of a community energy storage considering additional revenue streams and increased battery degradation?

We begin be reviewing related literature and establishing the identified research gap.

2 Related Work: Multi-Tasking Storage Applications to Enhance Profitability

In recent years, the stacking of services to enhance profitability of storage systems has been investigated in various settings, ranging from small household energy storage systems to applications in industrial plants and grid-scale storage systems with capacities in the magnitude of several Megawatt hours. A common finding is that the provision of ancillary services is a lot more profitable than trading on the spot markets (e.g., [6, 7]) but that in general, stacking services is beneficial due to higher utilization rates of the storage capacity. There are downsides as well, mainly the increase in cyclic degradation that depends on factors such as depth of discharge, overall throughput and temperature [8]. Consequently, the additional cyclic degradation differs for certain tasks. The authors of [9], for example, find that trading affects cyclic degradation more than provision of ancillary services due to very high and frequent depths of discharge.
The authors of [10] investigate parallel revenue streams in industrial applications and find that combining peak-shaving and FCR leads to larger profits than either individual task. Again, in an industrial setting, the authors of [6] extend these two tasks to include trading on the day-ahead and intraday spot markets and find that some companies may realize a positive net present value by combining all three tasks, although arbitrage trading is found to only add very little to the outcome. The authors of [11] compare

several technologies for the combined application of peak-shaving, self-consumption and trading on the day-ahead market in order to adhere to the previously sold energy profile of a wind turbines. They find that the prioritization of some use-cases, such as peak-shaving of an industrial user, can lead to additional benefits when sharing the BESSs capacity amongst several user.

Some studies dealing with multiple applications for storage systems model multi-energy systems, for example a distribution network section or a community where batteries and other flexible consumers can be used to balance the system, shift consumption to hours with lower electricity prices and provide ancillary services. In [12], the provision of secondary control reserves (aFRR) is combined with storing surplus PV generation to relieve congestion in the distribution grid. The authors of [13] minimize the costs of supplying a smart community in Australia with electricity that is simultaneously able to trade on the national wholesale markets and to provide ancillary services. In these studies, while BESSs are deployed for several tasks similar to our study, the concrete value for the battery service is not evaluated since the economic efficiency is considered from a system perspective. In practice, however, there is often no central system authority optimizing the system. Instead, the expansion of DERs and BESSs is driven by many independent actors who are incentivized to invest in these technologies by the market if they promise a profitable operation.

Several studies assess the profitability of residential, usually PV-coupled storage systems. For example, the authors of [3] deploy a BESSs for avoiding PV curtailment, shifting (peak) demand and increasing overall self-consumption, assuming a time-of-use tariff and electricity costs that include both energy and power related components. The authors of [14] optimize a community energy storage for the joint application of self-consumption service under a time-of-use tariff, congestion measures in the distribution grid and trading on the intraday market. For a profitable storage operation, these studies rely on the assumption of dynamic electricity pricing schemes that incentivize flexible and possibly network beneficial storage usage.

The combination of increasing self-consumption and providing ancillary services has also been addressed in various residential settings. The authors of [15] combine self-consumption and the provision of FRR in a residential community in the Netherlands. In [16], the authors show the trade-off between the provision of FCR and self-consumption and show that revenues can be increased by 25% in comparison to the most profitable single use-case. This multi-tasking deployment of household energy storages is already pursued commercially by the battery manufacturer sonnen GmbH, who offer a flat rate electricity supply model for PV-coupled BESSs in return for the right to use a small percentage of the storage system capacity to participate in the FCR auction [17].

Few of the papers cited here consider other motives for the installation of residential storage systems than profit maximization. While the profitability certainly remains the most important incentive, we suggest a prioritized management system for the deployment of a multi-tasking storage system that ensures the maximum provision of households with generation from rooftop PV and uses idle capacities to participate in the auctions for ancillary services and trading on wholesale energy markets.

3 Online Storage Operation with Prioritized Services

In this paper, we present a management system for the division of a stationary battery's capacity amongst several tasks. We assume that a community consisting of a number of households is equipped with several PV plants and a Community Energy Storage (CES). The capacity of the CES is divided amongst several tasks with different priorities. We assume that the motivation for the investment in the storage facility is the supply of self-generation from the PV roof top systems in the community. Therefore, this task is prioritized above the other applications. Providing ancillary services with the remaining capacities is regarded the second priority, while the trading task has the lowest priority amongst all service since it promises low profits and high effects on battery aging. The strategy includes a multi-stage decision-making process to ensure that the primary task of self-consumption is prioritized. On the other hand, it also ensures that the bids that the storage facility makes on the energy and ancillary markets can be met during operation. The revenue streams that are considered are explained below.

3.1 Revenue Streams

Self-Consumption of Generation from PV Plants

Under the current regulation in Germany, a household with a PV-coupled BESS can use its storage system to increase self-consumption from solar generation without additional charges. Therefore, increasing self-consumption is a viable option to generate revenues from BESSs. In this paper, we assume that this applies to a small neighborhood with a shared CES as well, which is currently not the case under German regulation [18].

Provision of Ancillary Service

Secondary to self-consumption, the CES in our model can participate in the FCR and aFRR auctions. Although the storage in our model is not large enough to participate in these markets on its own, we assume that it is part of a virtual plant that meets the prequalification criteria to provide ancillary services, similar to the service provided by sonnenGmbH. Since July 2019, the auction for FCR has been held two days before the delivery period during the week and three to four days before for the services delivered on Sunday through Tuesday [19, 20]. FCR is tendered symmetrically and must then be available over a period of 24 hours [21]. In the case of the storage management presented in this paper, we model this requirement by reserving double the capacity in the storage than what has been offered at the auction. This ensures that with an adequate control strategy, both positive and negative FCR can be provided by the CES at all times. On the other hand, positive and negative aFRR is auctioned separately and thus only the actually offered capacity is reserved in the CES. The auction for six time slots with a duration of four hours each of aFRR provision takes place on the day before delivery at 8 AM [22]. For the participation in the auctions for FCR and aFRR, we assume that the bid of the storage is always accepted. While the provision of FCR is rewarded with a uniform clearing price that we include in our model, the aFRR auction is conducted according to the "pay-as-bid" principle. We therefore use the average capacity price to remunerate the aFRR provision.

Trading on the Day-Ahead and Intraday Market

The CES is further able to trade electricity on the day-ahead and intraday spot markets with the restriction that only electricity that is previously bought on the wholesale markets can be sold there again. Therefore, trading on wholesale markets cannot be used for self-consumption and vice versa. This is plausible for regulatory reasons since we assume that network charges are not applied on the trading activities while household electricity consumption is subject to all usual taxes and levies. Note that this business model is not feasible under current regulation, however we assume in this paper that an aggregator could realize the participation in all markets considered provided that the tasks are strictly separated. For the trading activities, a perfect foresight of market prices is assumed in all models. Since potential revenues from arbitrage are generally low and cyclic degradation has been shown to be higher for trading activities [9], this task has the lowest priority in our management scheme and the assumption has, therefore, little impact.

As mentioned above, under current regulation the combination of the here considered tasks is not feasible. However, BESSs have great potential to address the increasing need for flexibility in energy supply. PV-coupled storage systems can help to reduce congestion on network sections in the distribution grids by buffering peak generation. The provision of ancillary services is important for the system stability as well and the increasing participation of BESSs in the FCR market has already led to decreasing prices due to their fast ramping times and low marginal costs [23]. The same is not necessarily true for the trading activities on the wholesale markets since these can be counterproductive to local network stability. However, in this case, the prices of the wholesale markets could be replaced by nodal pricing signals that reflect local network congestion situations. The management algorithm presented in this work could still be applied. Regulatory adjustments of spatial market signals are therefore urgently needed to further stimulate the installation of BESSs and to fully exploit the advantages of decentral storage systems.

3.2 Storage Operation

The task of the CES management system is to allocate the capacity of the storage to multiple tasks with different priorities. Battery storage capacity faces a series of decisions over different time periods as illustrated in Figure 1. We use a hierarchical approach to schedule the storage tasks, assuming that enhancing self-consumption is desired by the community and thus prioritized over the other two tasks. Therefore, the first decision the CES faces is how much capacity to withhold for the prioritized task of maximizing the self-consumption of the households in the community with generation from the rooftop solar PV panels. At the time of the FCR auction, the storage management system has reserved the capacity it needs to supply household loads. The bid on the FCR market is thus the minimum of the resulting idle capacity that it can offer continuously throughout the 24-hour delivery period of D, cap_D^{idle} and the power rating of the storage system $power^{CES}$. On the subsequent aFRR auction the battery storage again bids the maximum of the capacity that it can deliver for each 4-hour time slot S in day D, $cap_{S,D}^{idle}$, considering both reserved capacity for self-consumption and the already scheduled bid on the FCR auction. For each time step, the bids on the ancillary markets combined cannot exceed the power rating of the storage. This scheduling approach for ancillary services is schematically pictured for a time period of two days in the illustrations on the right side of Figure 1. Note that for the determination of the bids on the FCR and aFRR markets, the idle capacity is in the unit kWh and has to be converted to the corresponding power that can be offered. For FCR, the storage operator has to be able to provide the power that she bids on the auction for up to 15 minutes. Since we reserve double the capacity to ensure the symmetric provision of FCR, the idle capacity has to be divided by two and then multiplied by four to result in the corresponding power bid. For example, if the idle capacity of the storage is 20 kWh, then 40 kW can be provided for the duration of 15 minutes because 40 kW * 0.25 h is 10 kWh and to ensure provision of both positive and negative FCR we reserve 20 kWh.

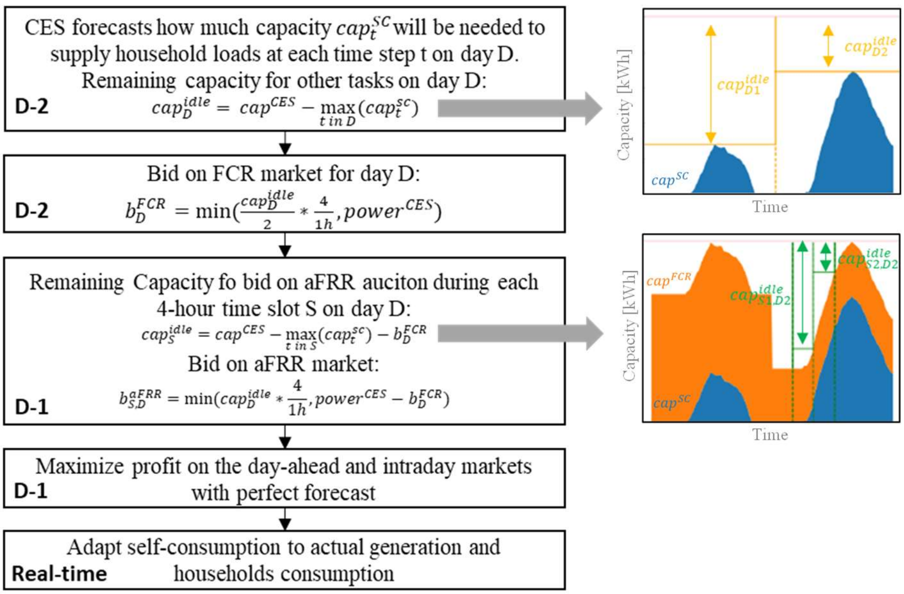

Figure 1: Sequential decision-making of the CES

During the first decision on how much capacity should be reserved for the self-consumption of households, the storage facility distinguishes between phases with several consecutive sunny days, cloudy days, or a mix of both. During “good weather periods”, i.e., several consecutive days with high PV generation, the daily electricity consumption can be substantially lower than the daily PV generation. Therefore, if another day with PV generation is expected for a following day, the storage is only charged with generation from PV until the expected overnight load can be supplied. This leaves room for capacity that can be offered on the ancillary service and energy markets. Only if a day with low PV production is expected to follow a "good weather period", the storage is maximally charged with PV generation to ensure full exploitation of self-consumption. Figure 2 illustrates the effects of the described management heuristic during a seven-day period with a transition from a "good weather period" to a "bad weather period" between day 4 and 5. It is evident that the consideration of maximum overnight load and transition from "good" to "bad weather periods" significantly increases the available capacity for other tasks than self-consumption and it especially affects the ability to provide FCR due to the longer delivery periods.

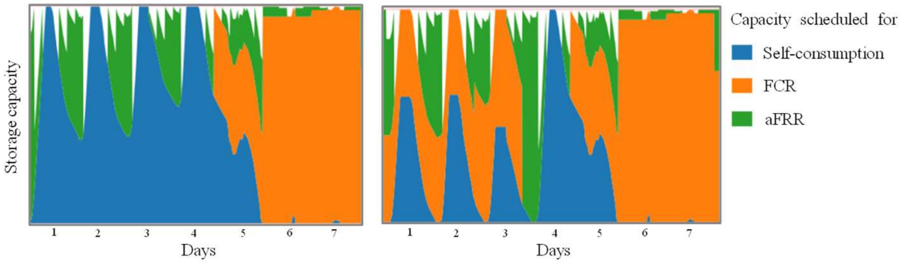

Figure 2: Allocation of storage capacities without (left) and with (right) consideration of overnight household load during four days with PV generation followed by two days with no generation

In addition to the tasks of self-consumption and the provision of ancillary services, the CES may use idle capacities to trade on the day-ahead and intraday spot markets. Since the auctions for these services are after the FCR and aFRR auctions, the storage knows how much capacity has to be reserved for ancillary services. However, the storage must also know the exact course of the self-consumption curve so that the trading task does not interfere with the prioritized task. Since trading promises low profits at high risk, we assume a perfect foresight for this task to get an upper benchmark for the potential profitability of the trading task and provide an assessment of the trade-off between gains by the trading task and potential losses due to the interference with the self-consumption task in the evaluation of the case study. In this decision step the CES therefore optimizes its revenues on the wholesale markets with perfect forecast. Lastly, during the operation of the storage in real-time, the storage has to adapt to the previously uncertain household load and generation from rooftop PV. Since at this time, the bids on the ancillary markets have already been made, the capacity that is needed for the provision of these services is reserved and the self-consumption has to be adapted accordingly. This means that if the storage underestimated the households' overnight loads in the first decision step, it may then happen that not all loads can be served during the night, even though enough PV generation would have been available the day before. Similarly, if the overnight load is overestimated, it can happen that solar generation remains unused in the storage system, thus occupying capacity that could have been used for other services. We describe how the uncertainty of consumers load and PV generation is incorporated in the next section.

3.3 Modelling Uncertainty

In order to simulate the uncertainties in the operation of a PV-coupled storage system, we add noise to the future PV generation and household load, which the storage system uses to make decisions. For this purpose, we use the so-called Perlin noise [24]. Ken Perlin developed a noise in which the error in a sequence is based on the gradient of the previous error. This results in a random gradient that does not jump jaggedly like for example a Gaussian noise. The Perlin noise is especially suitable for a natural environment such as weather data. Since the decisions of the CES always refer to a period of time that extends over several simulation steps, in the case of Gaussian noise, the individual errors can cancel each other out. This is not the case when using Perlin noise. In our model, we differentiate between two different time horizons when adding noise. For the short-term decisions up to two days ahead of delivery, i.e., FCR decisions on weekdays and all later decisions, a "short-term" error factor with a standard deviation of 0.4 is multiplied with the actual generation or consumption. For the FCR decisions three and four days before delivery, a "long-term" error factor with standard deviation 0.8 is used. An exemplary illustration of the effect of the two error terms is shown in Figure 3.

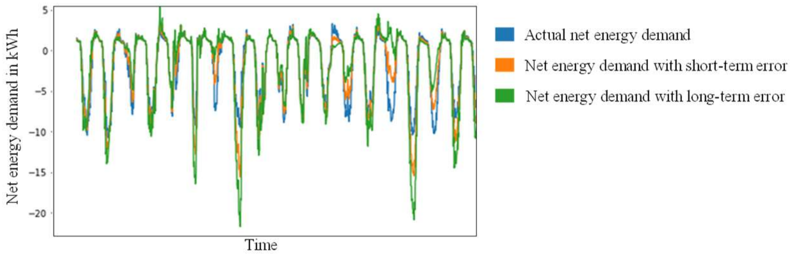

Figure 3: Comparison of actual net electricity demand (defined as daily generation minus daily consumption) with short- and long-term Perlin noise

3.4 Economic Evaluation

To compare the combination of different tasks under the proposed management scheme as well as the effectiveness of the prioritization of services, we calculate the net present value (NPV) of the CES in Equation 1. The initial investment I is subtracted from the annuities of the cashflow CF. Adapting the approach in [25] and [6], we account for the effect that the respective utilization has on the battery degradation by oversizing the storage capacity cap^{BESS} in the calculation of the initial investment in Equation 2. The effects of the State of Charge (SoC) and cyclic behavior of the CES is modelled in Equation 3. Drawing from the conclusion in [26] that the lifetime of an always fully charged BESS is reduced by one third, one third of the average storage level is added to the original battery capacity (Equation 4). Equation (5) expresses that a not fully exploited cyclic lifetime increases the calendric lifetime. Therefore, the capacity is reduced depending on the total electricity in-flow e^{total} which is the electricity that flows into the CES during one year caused by self-consumption and trading, plus a term that accounts for the electricity flow $E^{FCR,mean}$ per tendered MW of FCR based on information from [6] (Equation 6). For a more detailed description of this approach to account for battery degradation, please see [6]. The electricity in-flow caused by the provision of aFRR depends on the energy price that is bid during the auction and is thus not considered in this model. Since the capacity offered for aFRR is substantially lower than for FCR, this assumption has little impact.

$NPV = -I + CF * \frac{(1+i)^T - 1}{(1+i)^T * i}$	(1)
$I = cap^{oversized} * p^{CES}$	(2)
$cap^{oversized} = \frac{cap^{CES}}{EoL} + cap^{add} - cap^{red}$	(3)
$cap^{add} = \frac{1}{3} * \sum_{n=1}^{N} SoC_n * \frac{1}{N}$	(4)
$cap^{red} = \frac{1}{3} * (cap^{CES} - (e^{total} * \frac{lifetime_{calendar}}{lifetime_{cyclic}})$	(5)
$e^{total} = \sum_{d=1}^{365}((\sum_{t=1}^{96} e_{d,t}^{in}) + b_d^{FCR} * E^{FCR,mean})$	(6)

The annual cashflow that the CES realizes is calculated by summing over the daily revenues from self-consumption R_d^{SC}, ancillary services provision $R_d^{ancillary}$, and trading R_d^{trade} in Equation 7. The components are explained in the following.

$CF = \sum_{d=1}^{365}(R_d^{SC} + R_d^{ancillary} + R_d^{trade})$	(7)
$R_d^{SC} = \sum_{t=1}^{96} e_{d,t}^{SC} * (p^{el} - fit)$	(8)
$R_d^{ancillary} = b_d^{FCR} * (p_d^{FCR} - E^{FCR,mean} * p^{DA,mean}) + \sum_{b=1}^{6}(b_{d,b}^{aFRR} * p_{d,b}^{aFRR})$	(9)
$R_d^{trade} = \sum_{h=1}^{24}((e_{h,d}^{sell,DA} - e_{h,d}^{buy,DA}) * p_{h,d}^{DA}) + \sum_{t=1}^{96}(e_{t,d}^{sell,Intra} - p_{t,d}^{Intra}))$	(10)

Self-Consumption

The value of the electricity from PV generation that is temporarily stored in the CES and then used for self-consumption is the difference between the electricity price p^{el} and the fixed feed-in-tariff fit for generation that is fed into the grid. Without the storage, household load could be supplied at the uniform electricity price of 30 ct/kWh and excess PV generation could be fed into the grid for 10 ct/kWh. Therefore, every kilowatt hour that is consumed additionally is valued at 20 ct/kWh in the cashflow calculation. For the cashflow over the period of a year, the self-consumption in each 15-min interval is added up and multiplied with $(p^{el} - fit)$.

Ancillary Services

The profits on the FCR market are calculated by multiplying each days' bid b_d^{FCR} on the FCR auction with the respective clearing price p_d^{FCR}. Since we do not model the actual electricity flow of FCR provision, we include the average amount of electricity $E^{FCR,mean}$ that is demanded by the transmission system operators per auctioned kW of tendered FCR, subtracting it from the cashflow function. We assume that the necessary electricity for the provision of frequency control can be acquired on the energy markets and therefore price this energy at the average price for electricity on the day ahead market $p^{DA,mean}$ in the considered time period. The profits on the aFRR market are calculated similarly, summing over all six 4-hour blocks that are auctioned each day. Since aFRR provision is compensated not only with a capacity price but also with an energy price for each kWh that is actually requested by the network operator, we include no extra costs for the provision of aFRR but assume that the purchase of the required energy is compensated by the energy price.

Trading

The profits of trading on the energy markets are calculated with the electricity $e_{h,d}^{sell,DA}$ and $e_{t,d}^{sell,Intra}$ that is sold on the day-ahead and intraday markets, respectively, during each time period minus the electricity that is bought ($e_{h,d}^{buy,DA}$ and $e_{t,d}^{buy,Intra}$), multiplied with the respective prices $p_{h,d}^{DA}$ and $p_{t,d}^{Intra}$ at a given time step.

4 Case Study: A multi-tasking Community Energy Storage

To demonstrate the proposed management scheme and its implications on the profitability and utilization of a CES, we consider a community of ten households of which six participants possess a rooftop PV system with 10 kWp each. The community shares a CES of 50 kWh, which roughly corresponds to the size of six average installed household energy storage systems in Germany in 2019 [1]. The remaining four households are consumers who can consume electricity from the PV generation and stored electricity from the CES without additional charges. Table 1 shows the further assumptions of our model. For lithium-ion battery storage, manufacturers of current battery systems for residential use state calendric lifetime of 10 to 15 years and cyclic lifetime of 5000 to 10000 cycles [27, 28]. System investment costs for residential battery storage is assumed to be 800 €/kWh [23]. The end of life is assumed to occur when 80% of the battery's' initial capacity remain. To simplify the model, we neglect losses in efficiency.

Table 1: Case Study Assumptions, based on data from [6, 23, 27, 28] and own assumptions

cap^{CES}	50 kWh	Interest rate i	2%
$power^{CES}$	50 kW	$lifetime_{calendar}$	10
PV size	10 kWp	$lifetime_{cyclic}$	5000
Investment costs p^{CES}	800 €/kWh	$E^{FCR,mean}$	689.5 kWh /MW/day
End of Life (EoL)	80% of cap^{CES}		

4.1 Data

For the households in the community, we use real load profiles from a dataset of households in Berlin made available by [29]. To map the PV generation, a synthetic data set is obtained based on the methods from [30] and [31]. The data is scaled to the corresponding PV plant power in our model. The data set is available in hourly resolution and is linearly interpolated for the simulation into 15 minutes intervals. The price data of the day-ahead market is obtained from [32] for the year 2019. The same prices are used as an approximation for the prices of intraday trading as well. This inaccuracy is accepted due to the low profits from trading in general and to allow shorter trading intervals than on the day-ahead market. The results for the FCR auctions from July to December 2019 are obtained from [33], the platform for the tendering of ancillary services in Germany. The same source provides data for the aFRR market for the entire year of 2019.

4.2 Evaluation

As the data for the FCR auctions are only available for the second half of 2019, the six months from July to December 2019 are simulated for the case study. For the NPV and battery degradation calculations, we assume that the cashflow and cyclic utilization of the storage system in the simulation can be transferred to an entire year since the months under consideration cover all seasonality. We compare three strategies: (1) (naïve) self-consumption only, (2) self-consumption and provision of ancillary services and (3) self-consumption, ancillary services and trading. Figure 4 shows the resulting cashflows from the respective tasks for the six-month simulation and the net present value of each scenario.

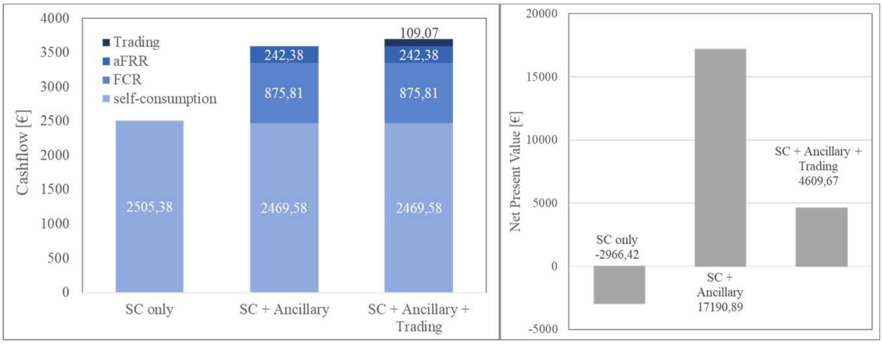

Figure 4: Cashflow during 6-month simulation for each task (left) and net present value in each scenario (right)

It can be seen that self-consumption is responsible for the bulk of income, which can be ascribed to the prioritization of this task. Ancillary service provision, and especially FCR, adds another significant revenue stream while the trading task contributes a relatively small proportion to the overall cashflow. We attribute the difference in the cashflows from self-consumption between scenario 1 and scenarios 2 and 3 to the prioritizing of services under uncertainty. In scenario 1, a naïve self-consumption strategy ensures the maximum exploitation of rooftop PV generation. At any time, excess PV generation is stored in the CES until the storage is fully charged. In scenarios 2 and 3 however, the scheduling of ancillary services under uncertainty leads to occasional under-estimations of storage capacity that have to be reserved for self-consumption. Since the provision of the bids on the ancillary markets has to be ensured at all times, this leads to some days where self-consumption cannot be maximized. However, the small difference in cashflows shows that this does not lead to significant impairment of the prioritized task of self-consumption. One way to entirely avoid these interferences would be to add an "uncertainty buffer" to the capacities that are reserved for self-consumption. However, due to the small magnitude of the interference it is questionable whether the trade-off with resulting losses in revenues from the ancillary markets could be accepted.

Table 2 shows the respective results of the battery degradation calculations, the average storage levels and electricity in-flow in the three scenarios. The specified in-flow values refer to the six-month simulation. Note that for self-consumption only, the battery simply charges excess PV generation whenever available and supplies households' loads whenever possible to ensure maximum self-consumption. This results in a high average SoC throughout the year, as overall PV generation is significantly higher than households' load. High SoC levels in turn increase the aging component cap^{add}, and subsequently the investment costs as well. If we assume that an intelligent management system can keep the average SoC at the same level as in scenario 2, the $cap^{oversized}$ value would sink to 58.23 kWh and consequently, the NPV for self-consumption only in scenario 1 would rise to -1574.42 €. Nevertheless, it is evident that self-consumption as only task cannot ensure a profitable storage operation in our use-case.

Table 2: Case study results

	SC	SC + ancillary	SC + ancillary + trading
Average SoC [kWh]	19.95	14.73	21.92
e^{SC} [kWh/a]	5612.31	5407.26	5407.26
$e^{trading}$ [kWh/a]	0	0	11838.32
cap^{add} [kWh]	6.65	4.91	7.31
cap^{red} [kWh]	9.18	8.33	-7.46
$cap^{oversized}$[kWh]	59.97	59.08	77.27
NPV [€]	-2966.42	17190.89	4609.67

While the trading tasks only generate a revenue of 109 € in the 6-month simulation, they immensely increase the energy throughput during the considered time period. This becomes evident in the aging parameter cap^{red} which turns negative, an effect that can be explained in the fact that over the lifetime of ten years, the CES cycles in scenario 3 would exceed the cyclic lifetime of 5000 cycles, thus reducing the calendric life instead of prolonging it. This is an undesirable effect that, in combination with the reduced NPV in scenario 3 compared to scenario 2, clearly indicates that trading should not be included in the tasks of the CES in consideration. On the other hand, both scenario 2 and 3 lead to a positive NPV in contrast to the single use-case in scenario 1, thus underlining the necessity of investigating multi-tasking storage deployment in residential settings.

5 Discussion

There are several limitations to our study that could be considered in future research. To reduce complexity, we provide a strategy for the scheduling of a storages' capacity amongst several tasks and neglect the actual power flows for the provision of ancillary services. Including this could cause interferences with the other tasks considered here. Nevertheless, we contribute a realistic approximation of the economic implications of the proposed multi-tasking business model.

For the trading task, we assume perfect forecast to receive an upper benchmark for the profitability estimation. Our case study shows that arbitrage trading on the wholesale energy markets would not be a feasible business model given current price spreads. Trading under uncertainty would further diminish the already negative revenues from arbitrage, and, even more importantly, likely interfere with the prioritized and more economic task of self-consumption. In the current market situation, we would therefore advise a storage operator against trading. However as mentioned before, local price signals could play a more important role in the future and should be investigated in future research.

A further possible limitation is the chosen method to account for storage degradation, as it penalizes the high cyclic utilization of the trading task immensely. Modelling storage degradation without actual measurement data is a complex matter in any case. However our results are in line with previous studies that have already shown that trading on the wholesale markets leads to higher losses in battery lifetime [9].

Future work should not only address the limitations listed above, but also further investigate the incentives for investing in BESSs in residential settings. Non-monetary drivers such as saving CO_2 emissions or achieving a higher level of autarky could further accelerate the adoption of BESSs and should be considered when designing operational strategies and incentive mechanisms.

Overall, this work contributes to a stream of research with growing relevance both in theory and practice. The versatility of possible applications of BESSs provides the ideal conditions for their increasing use in a wide range of environments. For possible investors, we demonstrate the profitability of combined tasks in a residential setting. For regulators, these findings are a call to design a regulatory framework that provides incentives for the wide-spread installation and deployment of storage technologies.

6 Conclusion

In this paper, we introduce an operational strategy that schedules tasks of a community energy storage with different priorities under uncertainty and adapts to changes in forecasted generation and consumption in real-time. In a case study, we show that this strategy largely succeeds in ensuring the prioritized task of self-consumption maximization while simultaneously realizing income from other revenue streams that ultimately lead to an overall profitable storage operation. We show that the stacking of services is extremely beneficial to ensure the economic operation of a CES in a residential setting. However, the realizable income from additional tasks has to be weighed against the additional battery degradation it may cause. In the case study at hand, the CES profits from the combination of self- consumption with ancillary services while trading on the wholesale markets decreased the overall net present value.

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Smart Energy Systems: A Multidimensional Literature Review and Future Research Agenda

Abstract.
Digital transformation, decentralization, and decarbonization of the energy sector are significant challenges for the next decades. Renewable energies and smart energy systems enabled by advanced information and communication technologies influence and transform, e.g., business models, customer behavior, governmental regulations, and technological innovations. However, there is still limited multidimensional research of future avenues for smart energy systems' digital transformation process. We conducted a systematic literature review facilitated by the PESTEL framework and a hierarchical clustering analysis to address this research need. We created a heat map to visualize research intensities in different areas, identified six critical topics in smart energy system research, and derived a future research agenda.

Keywords: PESTEL-Analysis, Hierarchical Clustering, Smart Energy Systems, Future Research Agenda.

1 Introduction

The mitigation of climate change is one of the significant challenges confronting global society. However, smart energy systems (SES) are a core enabler for decarbonizing the global energy sector and environmental protection [1-3]. A solution is integrating advanced information and communication technologies (ICT) in smart homes, buildings, neighborhoods, or quarters to support an efficient, local, and climate-friendly energy supply [4]. In this transformation process, technological aspects are of significant importance; they also include political, economic, social, environmental, and legal aspects, forming a demand for research. Moreover, current academic literature calls for the investigation of multidimensional perspectives and a holistically understanding of SES. Therefore, we address the following research questions (RQ):

RQ1: How does academic literature address SES along with the PESTEL (political, economic, social, technological, environmental, and legal) framework?
RQ2: Which research gaps and needs, as well as recommendations for future research directions, can be derived?

First, we describe the research design and methodology. Based on this, the literature review results along with the PESTEL framework and the hierarchical clustering are presented. Following this, we discuss the literature review results and the hierarchical clustering and integrate both research approaches in a heat map. Furthermore, the results of the heat map are derived as implications and recommendations for future research pathways. We complete the work with conclusions and limitations.

2 Research Design and Methodology

This study's research design is structured in three phases: first, literature review using the PESTEL framework [5], second, hierarchical clustering analysis, and third, the development of a heat map. The PESTEL analysis is a strategic management tool for companies to receive insights into the macro-environmental condition of the market and identify critical factors that constrain or promote a company's successful operation [5]. For this reason, the PESTEL analysis provides a general idea or overview of the macro-environment and has not the purpose of analyzing a situation in a detailed manner.

Literature Review: The application of the literature review is based on a systematic and keyword-based literature search [6, 7, 8]. For this purpose, we utilized the electronic database AISeL to include IS Journals and Conferences and cross-discipline sources such as ScienceDirect and Google Scholar. The usage of appropriate search terms is essential to identify relevant literature. Therefore, we used the keywords: "smart energy market" AND "information and communication technology" AND "digital transformation" OR "political" OR "economic" OR "social" OR "technological" OR "environmental" OR "legal". In total, the database search resulted in 6429 hits, which was reduced to 318 after limiting the publication years from 2010 to 2020, restricting the German and English language, and the peer-reviewed requirement. Following the review of the title, 138 articles and after reviewing the abstract and the keywords, 108 articles remain. In the next step, we classify the publications along with the different PESTEL factors: political, economic, social, technological, environmental, and legal. After full reading of the articles, 68 remain. We exclude literature that is too technical, a full text is not available or unrelated to our research focus of a multifaceted and inter-and transdisciplinary perspective. To evaluate our references, we conduct a backward, forward, and author search [9]. Subsequently, we did a Google Scholar similarity search with our most relevant papers found so far [e.g., 4] to determine related articles. After finishing the literature review, 77 publications were identified in total. Subsequently, the dataset of 77 papers was analyzed according to their relevance to the individual PESTEL factors. Here, each paper can be associated with either one or more PESTEL factors.

Hierarchical Clustering Analysis: Then, we performed the hierarchical clustering analysis using a python based text mining tool[1] to identify articles' clusters and, hence, receive critical topics [10]. We apply the ward method to the hierarchical clustering

[1] https://orangedatamining.com/

analysis data, which calculates the distances between all articles. Based on this, we visualized the results in a dendrogram to identify the clusters graphically [11].
Heat Map: To create the heat map, all publications related to a particular cluster were plotted on the vertical axis and classified according to the respective PESTEL factors within their clusters. Thus, the heat map is vertically oriented to the identified clusters and horizontally oriented to the PESTEL factors.

3 Results

3.1 Literature Review

Political factors are European and national laws and the economic impacts that arise, e.g., from subsidies and taxes in the execution of the European Green Deal or the German renewable energy law [12, 13].
Economic factors include the participation of start-ups and companies from non-energy sectors in the energy market. They bring innovative technologies and novel business models (BM) to the market. For example, demand response, peer-to-peer (P2P) energy trading, virtual power plants (VPP), dynamic tariffs, smart home, and energy efficiency services [14-16]. The P2P concept, which initially was developed in the financial sector, is also increasingly used in the energy sector. The peers, small energy producers, prosumers, and consumers can trade directly on a platform without intermediaries. Companies that follow the P2P principle are, e.g., Sonnen[2], Buzzn[3], and Polarstern[4], which provide energy trading platforms, smart storage systems, and renewable energy tariffs [14]. However, many existing energy utilities are also entering into the virtual energy business and offering virtual storage clouds and e-mobility services. These opportunities are valuable if customers cannot afford the high investments required for energy generation and storage facilities. Hence, photovoltaic power plants and storage systems are also offered under a long-term contract [14, 17].
Social factors are user acceptance, environmental behavior, privacy concerns regarding data use, profiling, and the increasing participation of third parties in the energy market [18-20]. Energy-related services, which support smart meters and flexible energy prices, encourage consumers to save energy by reducing energy costs [4, 20]. Regarding privacy, energy data is highly sensitive since it enables identifying daily routines in the household. The peaks in energy consumption can be used to determine, e.g., when a meal is cooked [19].
Technological factors are developing and integrating energy management systems to allocate energy demand and consumption sustainably and at minimum costs. With the expanding share of renewable energies in the energy system, the significance of storage technologies, such as batteries and virtual storage, increases [4, 21]. However, households can participate in a local energy market by selling flexibilities in times of

[2] https://sonnen.de
[3] https://www.buzzn.net
[4] https://www.polarstern-energie.de

high electricity prices or purchasing loads at low energy prices through storage facilities or vehicle-to-grid concepts [22]. However, cyberattacks, data breaches, malfunctions, or failure of a component can severely impact the cyber-physical system and, therefore, reliability supply, company reputation, and user acceptance. In addition to the monitoring, transmission, and storage of sensitive data, monitored with smart meters, the physical system of energy supply and its infrastructure is a significant target and triggers security concerns. The mitigation of these vulnerabilities calls for technological, legal, economic, and user habit changes [23].

Environmental factors are international climate and sustainability goals and the increased energy consumption and recycling of batteries and smart devices [18, 21, 24]. Therefore, an increasingly significant issue is the rising diffusion of smart energy devices. Until 2025, 1.7 billion smart and networked devices throughout Europe are expected. These are mainly smart home appliances, which are permanently on standby and process data in cloud services or server centers. ICT, data centers, and servers consume energy progressively. Collected data needs to be uploaded, processed, and analyzed. Consequently, an increasing number of networked ICT can cause additional energy consumption of 70 terra watt-hours. For Germany, the additional electricity consumption of 15 terra watt-hours can be expected [26]. Waste and recycling management, especially electric batteries and ICT, due to the increasing diffusion and the need for storage capabilities and smart devices, is a significant challenge for the upcoming years [25, 27].

Legal factors are mainly concerned with the institutional implementation of laws and measures set by politics. The energy transition in local energy communities and municipalities requires public actors and role assignments [25]. Another factor is the lawful processing of personal data, determined by the European General Data Protection Regulation (EU-GDPR) [28].

3.2 Hierarchical Clustering Analysis

The dendrogram identified six clusters based on the hierarchical clustering analysis, which can be implied as critical topics (see Fig. A1 in Appendix). The respective papers were analyzed to identify the common features underlying their membership in a particular cluster to identify the individual clusters' implications. The following six clusters were identified as energy transition, smart services, acceptance, Green Information Systems (IS), Blockchain, and data analytics (top to bottom). The cluster energy transition includes the political framework conditions and barriers, and critical success factors (CSF) in integrating intelligent systems and renewable sources in energy grids [4, 29-33]. Smart service includes novel BM, stakeholders, energy trading activities, and other dynamics arising from digitalization and decentralization [12, 15-17, 21, 22, 25, 28, 34-50]. Acceptance is about social concerns and behavioral patterns on increasing intelligent devices' penetration in households [18, 19, 26, 51-65]. Green IS includes the research towards sustainable development and sustainable life cycle assessment (LCA) of novel BM and the transformation of established BM towards a more sustainable direction [66-76]. A key instrument, which is increasingly used in energy market, is Blockchain technology. It enables trusted, secured, automatic, verified, encrypted, and finalized trading activities without an intermediary for consumers, prosumers, wholesalers, and other market participants. The most frequent energy sector applications are electricity trade, grid service, green electricity certification, charging infrastructure, and asset management [77-80]. Data analytics is about Big Data utilization to receive optimization opportunities, business values, security and privacy aspects [23, 81-90].

4 Discussion, Implications, Recommendations, and an Outlook

The heat map, as illustrated in Fig. 1, serves as a basis for the discussion. Fig. 1 visualizes the research intensity in connection with the PESTEL factors and the six clusters. The research intensity ranges from blue (cold, only a few publications) to red (hot, many publications). The heat map's red fields do not indicate that research in these areas is saturated, while blue fields do not imply research needs. It is essential to ensure research needs, regardless of the amount of research conducted in this area or not.

	P	E	S	T	E	L
Energy transition	2	4	2	3	2	3
Smart services	7	15	4	15	3	5
Acceptance	1	3	12	5	0	3
Green IS	3	7	6	2	6	5
Blockchain	0	3	0	4	0	0
Data Analytics	0	8	5	7	0	1

low → high

Number of publications

Figure 1. Heat map

Economic, social, and technological factors have a high research intensity, whereas political, environmental, and legal factors have a lower one. The intensity in the clusters is high in smart services and acceptance, while the intensity is more limited in the energy transition, Blockchain, and data analytics. This implies that novel technologies in connection with SES have been investigated to a limited extent. A future research agenda can include taxonomies or maturity models in Blockchain and Big Data applications in the energy market. CSF analysis can also provide benefits for researchers and practitioners to identify which new disruptive technologies can enhance their own BM and bring additional value for stakeholders and customers. There is also a risk that BM loses value due to disruptive technologies, that their value creation process or service can be replaced by automation and offered at a lower cost. Besides, Blockchain and Big Data technologies have not yet been comprehensively examined at the legal and political level, so the legal framework for companies and their services regarding data protection has not been sufficiently analyzed and discussed. Possible research avenues could include a data protection investigation according to the EU-

GDPR and national laws of new technologies and novel players whose BM is essentially based on those technologies. Furthermore, smart energy governance should be further explored to fill the research gap and address research needs in the political and regulatory framework. A limited level of research effort in sustainability contribution and audit has been conducted to date. SES and their BM are, by definition, a sustainable solution for the transformation of energy systems. However, the question arises, what are the actual and perceived benefits for environmental, social, and economic sustainability, and why are these services more sustainable than other comparable services? Future research must increasingly focus on the combination of smart energy services and sustainability LCA. In the context within the analysis, economic aspects, such as new BM, start-ups, and decentralized energy trading platforms, are CSF for integrating SES. Economic benefit, profit, and stakeholder value are CSF for the integration of SES. Social aspects, such as acceptance and privacy concerns, constitute CSF. Consumers with a positive attitude will use and recommend renewable energy systems and smart energy services if they recognize a unique benefit for themselves, whether in financial or sustainable terms.

5 Conclusions and Limitations

According to the multidimensional literature review and the hierarchical clustering analysis, we have created a heat map to examine research gaps and guide the way to a future research agenda. Therefore, we identified six critical topics in the field of SES. Limitations lie in our reviewing process, identification of the PESTEL factors, and their interpretation. We are aware of the afflicted subjectivity during our research process. To reduce this, we applied the text mining technique to identify critical topics without the authors' subjectivity or personal bias. Main research gaps and needs were identified in new technologies and their applications and sustainability impacts in SES and legal and political frameworks, such as data protection. In this context, it is essential to focus on the holistic and multidimensional perspective to discover new connections, identify research gaps and needs, and strengthen the exchange between different disciplines. Besides, research, practice, legislation, and administration must be integrated into the scientific and public dialogue. Given the limited amount of relevant articles dealing with multidimensional CSF, further research is required to gain an in-depth interdisciplinary understanding of the relationships and dependencies, drivers, and barriers in SES, enabling a successful digital transformation.

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Appendix

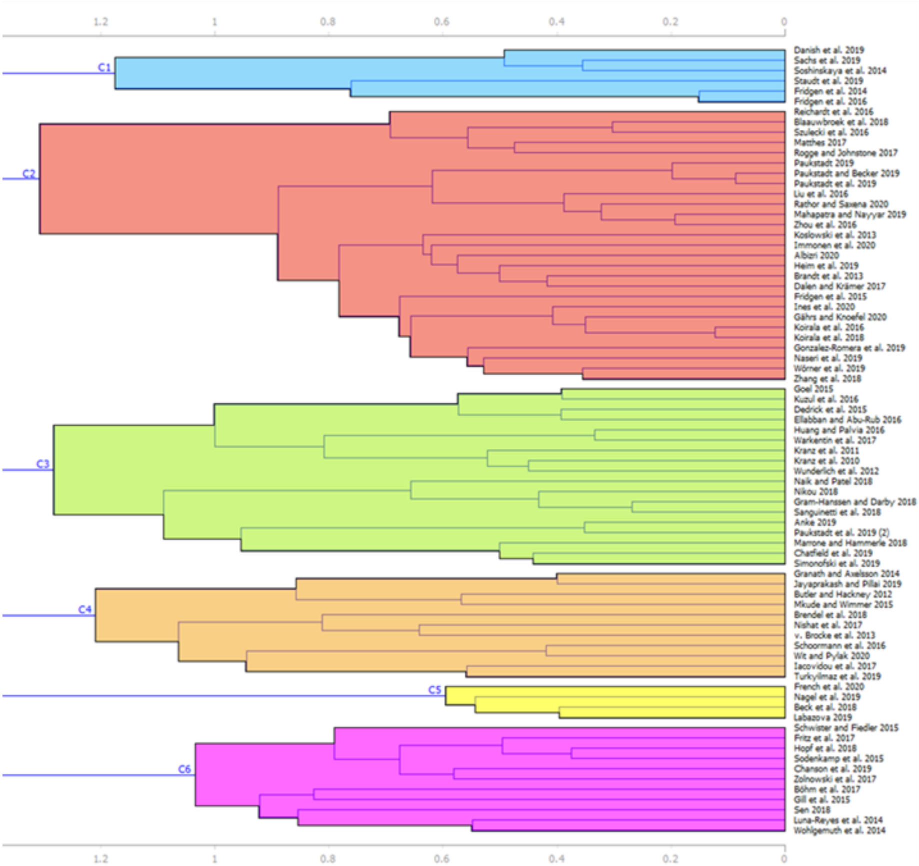

Figure A1. Dendrogram of the hierarchical clustering analysis

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A Sketch of Unwanted Gaming Strategies in Flexibility Provision for the Energy System

Abstract. Market-based procurement of system services is underway. Flexibility markets, however, are subject to a gaming risk. Different market participants can deteriorate the grid condition by their market behavior or physical actions, to generate flexibility demands and therefore potential profits, resulting in unreliable and unstable grid operation or economic inefficiencies. Such strategies are referred to as gaming. We investigate three gaming strategies regarding congestion management, reactive power management and balancing power provision. Further, we evaluate these strategies, and discuss solution techniques.

Keywords: Ancillary services, energy services, flexibility markets, inc-dec gaming, baseline scenarios.

1 Introduction

In the framework of the digital transformation of the energy sector and increasing decentralized feed-in of renewable energies, the provision of system services to ensure power system reliability, adequacy and stability will be a significant challenge for the next decades. A trend of market-based procurement mechanisms is further reinforced by the Clean Energy Package of the European Union [1, 2]. However, flexibility markets lead to gaming potential in congestion management, reactive power management, and balancing reserve. Unit operators can act strategically to create problems in the power system and profit by providing the flexibility to solve the self-induced problem. As main contributions, we present three gaming variants, perform a comparison, point out pilot projects and legal aspects with regard to monitoring as a countermeasure. The execution of gaming strategies can result in economic inefficiencies and hazards to the critical infrastructure. Research demand arises especially concerning the identification, analysis, and mitigation of these gaming strategies.

2 Gaming Strategies

2.1 Congestion Management

Increase-decrease gaming (inc-dec gaming) refers to a bidding strategy of market participants in a two-tier market system. The two-tier system features a zonal power market for trading electricity and a second, regionally more restricted market for the procurement of flexibility for the purpose of congestion management. Even though the two markets are functioning independently from one another, the bidding behavior on one market can directly affect the other market. When the bidding behavior on the zonal spot market results in network congestion, network operators would have the option to rely on flexibility from the flexibility market for the purpose of congestion management.

Inc-dec gaming exploits these interdependencies by exacerbating situations of congestion through accordingly adapted bidding behavior on the zonal market. This is done to generate windfall profits on the flexibility market through contrary bids [3].

In order for an inc-dec gaming strategy to succeed, market participants have to rely on accurate forecasts on the occurrence of a network congestion. The better the forecast, the lesser the risk of failing the inc-dec strategy, which would result in financial loss for the flexibility provider. Especially regarding structural congestions, a correct anticipation of market participants has to be considered. However, the learning curve for correct anticipation of grid congestions grows with each redispatch participation and can be further supported by specialized software tools, which provide better prediction results even for short-term congestions [3].

The gaming strategy varies with regard to the location of the optional flexibility being "in front of" or "behind" the network bottleneck as well as with regard to the facility type being either generation or demand response flexibility.The most relevant variation is an active approach of inc-dec gaming. On one hand, operators of generation flexibility in the electricity surplus area "in front of" the congestion, can price themselves into the spot market below their marginal costs. On the other hand, operators of demand flexibility in the scarcity area can increase the market demand by generating extra bids. This active approach of inc-dec gaming is driven by the expectation of additional revenue resulting from selling a "buy-back" option on the flexibility market regarding the previously sold electricity or demand offer. This approach results in economic inefficiencies without generating any additional positive effect for congestion management [4].

To be able to detect and penalize inc-dec gaming, market monitoring ideas are discussed. A baseline can continuously gather data of market participants with regard to their expected schedules [5]. Deviations from previously registered schedules can serve as an indication for the exercise of gaming. Another subject of discussion is an extension of long-term service products for the use of flexibility [6].

2.2 Reactive Power Management

A similar strategy to inc-dec gaming is possible in local reactive power markets in distribution systems. Reactive power needs to be procured locally close to the problem location — for example, a voltage violation — since it cannot be transported over long distances [8]. Most concepts for local reactive power markets are similar [7, 8, 9] and expect that the unit operators send an expected payment function to the grid operator, describing how much remuneration they demand for reactive power provision. The grid operator collects all offers and determines the optimal reactive power provision that minimizes costs, considering constraints, such as the voltage band, and the unit locations within the grid. Finally, the unit operators provide the requested reactive power and receive corresponding remuneration.

However, such local reactive power markets enable exploitation similar to inc-dec gaming. Flexibility providers are incited to actively induce system constraint violations close to their own units, then provide the countermeasures, and get paid for it to maximize profit. In contrast to inc-dec gaming, the violation is not induced by market behavior, but by physical actions of units that do not participate in the market, such as controllable loads in the distribution grid. Synchronized behavior of multiple such units, controlled either by a single agent or by a coalition of multiple unit operators, can add up and induce voltage and power flow changes into the grid beyond control of the grid operators. After violation induction, the problem solution in form of flexibility is offered by other units that participate in the local flexibility market, such as photovoltaic systems, at a high price corresponding the artificially increased demand. To the best of our knowledge, this strategy has not been described in literature yet.

The actual threat of this behavior regarding grid stability and monetary costs is still unclear since we describe it the first time here. We expect these strategies to be possible in power systems that are operated close to their system boundaries, because this facilitates to induce constraint violations more easily. Furthermore, these strategies can be expected if the grid operator is dependent on system services from few external partners, e.g. if the grid operator has no own units for reactive power compensation. However, large-scale simulations of different power systems in combination with flexibility market models are required to systematically search for such weaknesses and respective countermeasures. A capacity market that remunerates reactive power capacity instead of actual reactive power feed-in could be such a countermeasure.

A possible non-technical countermeasure could be extensive monitoring of power consumption of all units and checking for synchronized behavior. However, that would include private households, which requires additional consideration of data privacy and cyber security aspects.

2.3 Balancing Reserve and System Imbalance

A different gaming strategy is faced at the mechanism for accounting imbalance energy. Distributed energy resources (DER) can change their power schedule to provide balancing power or compensate balancing groups even on short notice [10-12]. Despite recent regulatory changes by the German Federal Network Agency [13] against strategic behavior of balancing responsible parties (BRP) that anticipate low imbalance prices and high spot market energy prices [14-18], there still exist interdependencies on the balancing reserve market, due to which it can be profitable to keep balancing groups imbalanced. Gaming can occur in quarter hours, during which the following conditions are met:

1. there is a lack of energy in a BRP's balancing group,
2. there is a lack of energy in the overall system, and
3. the BRP, being a balancing service provider (BSP) as well, has been contracted to provide positive (e.g. secondary) balancing energy.

Originally, in such situation, the BRP is incentivized to reduce demand or increase generation to compensate its unbalanced balancing group. If the system operator now requests a part of the contracted balancing energy, the BRP/BSP can increase the probability of selling all of its balancing energy by stopping the compensation for its balancing group. Through the partial request, the BRP/BSP receives the information, that its devices have direct influence on the overall imbalance of the whole system. If in such cases, the settled balancing reserve price is higher than the expected imbalance price, the BRP/BSP can earn the difference between both prices and might save compensation efforts. The same applies to a scenario in which there is too much energy in the balancing groups and the overall system, in combination with negative balancing reserve.

The BRP/BSP risks that all of its balancing energy would have been called forward, even without its own intervention. In such a case, additional imbalance energy has to be paid. Furthermore, the transmission system operator (TSO) could cancel the balancing group contract, if gaming is detected.

Today however, such behavior can be hidden in measured load and generation profiles of 15-minute resolution. Short-term changes in power schedules of flexible devices alter these average power values only slightly. Battery storages can even counterbalance changes of their desired power values within a 15-minute accounting interval. No data is collected at all, if flexible devices are located at customers without power measurement. Thus, more data from energy supply companies like setpoint changes would be needed to estimate the frequency and effect of this gaming approach.

In contrast to both previous approaches, the locality is not relevant. Like the creation of voltage band violations but different to inc-dec gaming, this behavior does not only manifest in registered schedules but would be induced in the physical power system. The described behavior can jeopardize grid stability and lead to increased economic costs. Measures against this gaming strategy could be a comparison of data from control actions of DER with time series of balancing reserve activations. To the best of our knowledge, this gaming strategy has not been described in literature yet.

2.4 Comparison of Gaming Strategies

All three strategies are based on the possibility of market participants to cause or intensify a problem in the system through their behavior and capitalize flexibility as problem solution. In addition to this, all three strategies are facilitated by market power. The following Table 1 summarizes the differences that we derived and discussed in sections 2.1 - 2.3.

Table 1. Comparison of gaming strategies

	Inc-/dec-gaming	Physical inducing of constraint violations	Maximize balancing reserve provision
Field of gaming	registered energy market schedules	physical constraint violation	short-term balancing group compensation
Profit mechanism	local flexibility market	local reactive power adjustment	increased balancing energy provision
Failing mechanism	possible risk through wrong forecasts; grid operator may buy flexibility elsewhere	grid operator may buy flexibility elsewhere	balancing reserve called anyway
Practicability	flexibility market required	flexibility market required	possible in current market design
Locality	relevant	relevant	not relevant

3 Monitoring as a Solution Approach

At present, practical implementations for gaming in balancing reserve and reactive power markets do not exist. However, there are several pioneer projects that have implemented flexibility markets, e.g.: Enera, Piclo Flex, GOPACS, and NODES. All these projects apply a baseline, (see 2.1) but have different approaches towards the technical designs and are operated on a platform by third parties [19]. Piclo Flex applies a standardized baseline, which consists of representative historical data. GOPACS applies prognoses as baseline, based on schedules, which are reported by the flexibility provider on the previous day. Enera and NODES apply baselines in dependence of the underlying network operator and technology. All projects are operated on a platform by third parties (large power exchanges in Europe or new market entrants). Besides, there is no penalty in case of non-delivery, although Enera cancels the contract after three events while the other projects consider penalties in terms of expansion [19]. This offers the opportunity to discuss monitoring as one example of a solution.

From a legal perspective, the legitimacy of data processing for purpose of monitoring will depend not only on the purpose of the data processing, but also on the specific design of the market, the type of sanctions – if any – and on the monitoring institution. As long as the baseline is used for compensation after a transaction, it likely falls under the justification of Art. 6 (1) lit. b) GDPR (performance of a contract). Monitoring however is not directly necessary for fulfilling the contract between the flexibility provider and the network operator, so that the applicability of Art. 6 (1) lit. b) GDPR at least stands in question [20, 21]. Similarly, it seems unlikely, that a market participant who intends to engage in gaming is willing to give consent (Art. 6 (1) lit. a) GDPR) to the data processing for monitoring. Furthermore, the operator of a flexibility platform also has an interest in preventing gaming, but once again, it is questionable whether monitoring measures by the platform operator are sufficiently directly linked to the contract for using the platform. Lastly, national regulations including penal regulations can have an impact on the extent to which data can be processed, Art. 2 (2) lit. d) GDPR and Directive (EU) 2016/680. While, all these considerations should be taken into account when designing the layout of monitoring measures, they should be considered as a possible solution.

4 Conclusions and Future Research Agenda

Three different gaming strategies in the market-based procurement of system services were presented and compared. Two of these strategies have not been discussed in literature yet. After identifying the ability of flexibility providers to actively influence demand for flexibility as a common underlying problem, which possibly can be addressed through market monitoring, pilot projects already using this approach were presented briefly.

Further research, not only regarding the legal aspects of such measures but also regarding economic and technical aspects is necessary. Furthermore, a simulative demonstration of the gaming strategies and countermeasures would be highly desirable.

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Towards a Decision Support System for Cross-Sectoral Energy Distribution Network Planning

Abstract. Requirements for energy distribution networks are changing fast due to the growing share of renewable energy, increasing electrification, and novel consumer and asset technologies. Since uncertainties about future developments increase planning difficulty, flexibility potentials such as synergies between the electricity, gas, heat, and transport sector often remain unused. In this paper, we therefore present a novel module-based concept for a decision support system that helps distribution network planners to identify cross-sectoral synergies and to select optimal network assets such as transformers, cables, pipes, energy storage systems or energy conversion technology. The concept enables long-term transformation plans and supports distribution network planners in designing reliable, sustainable and cost-efficient distribution networks for future demands.

Keywords: decision support system, distribution network planning, sector coupling, cross-sectoral energy planning, energy transition

1 Motivation

Middle- and low-voltage energy distribution networks are responsible for the reliable transport of generated energy to end users. Distribution networks are expected to play a decisive role for the successful integration of decentralized renewable power sources (e.g., wind energy, photovoltaics, and biomass). The principal challenge is coping with highly volatile energy yields of renewable energy sources in order to avoid critical feed-in peaks [1]. Additionally, on the load side, distribution network operators have been simultaneously confronted with an increasing maximum withdrawal capacity for several years. One reason for this can be found in the electrification of the transportation sector. In the future, distribution networks must fulfill new requirements of dynamic consumers like electric vehicles, which may cause possible violations of statutory voltage limits [2].

New asset technologies such as micro combined heat and power plants, power-to-x technologies, and energy storage systems are promising flexibility options for distribution networks to meet these challenges. They allow planners and asset managers of distribution network operators to utilize synergies between different energy sources and thus make energy systems more cost-efficient and less CO_2-emitting, while at the same time ensuring the stability of the networks in the future. However, planning complexity increases significantly due to the cross-sectoral design of energy transport, storage, and conversion, thereby placing new demands on planning procedures. Although simulation and optimization techniques are already used in a variety of contexts in individual sectors, very little literature exists to guide decision makers in selecting the right long-term transformation plans for integrated energy distribution networks. In this paper, we therefore introduce a conceptual decision support system (DSS) for the cross-sectoral optimization of energy transport, storage, and conversion, which enables distribution network planners to design reliable, sustainable, and cost-efficient distribution networks for future demands. The transformation plans proposed by the DSS align network capacity with expected loads across multiple scenarios while minimizing key performance indicators such as capital and operational expenditures in Euro, and CO_2-emissions in tons. The DSS concept has been discussed and validated with distribution network operators and additional domain experts as part of the ongoing research project *FlexiEnergy*[1].

2 Requirements & State of the Art

The challenges described in the previous section translate to the following requirements for a decision support system facilitating cross-sectoral distribution network planning:

R1: The DSS must consider all energy and demand sectors to maximize utilization of synergies between sectors and consequently achieve high decarbonization.

R2: The DSS must support uncertain future developments to help with investment decisions as distribution network assets have a long lifespan (ten or more years).

R3: The DSS must support a high temporal resolution to model technologies such as RES-based energy generation or charging and discharging of energy storage systems.

R4: The DSS must support a high spatial resolution for the assessment and optimization of individual network assets to ensure reliability and cost efficiency.

We filter the overview of modeling tools for energy systems given by Ringkjøb et al. [3] to identify the state of the art in cross-sectoral distribution network planning. Based on the above requirements, we only consider tools that focus on scenario-based investment decision support and support a modeling horizon of at least 10 years (R2), a temporal resolution below “Daily” (R3), and a spatial resolution below “National” (R4). We extend the resulting list of tools ([4–6]) with tools that are described in academic literature published in 2018 or later to account for recent research advancements. For this purpose, we queried *Web of Knowledge* for “ALL=(("decision support" OR "model" OR "tool") AND ("sector coupling" OR "cross-sector") AND "energy")” and included suggestions of reviewers ([7]). However, after manually filtering references that obviously do not align with the use case of cross-sectoral energy network planning, we find that all remaining tools either provide none or only partial cross-sectoral coverage ([4, 8]), do not focus on long-term, optimization-based

[1] https://flexi-energy.de/en/

investment decision support ([5, 9–17]) or do not possess the required spatial resolution needed for distribution network planning ([7, 18–25]). Consequently, to the best of our knowledge, no available system sufficiently supports decision makers in cross-sectoral distribution network planning.

3 A Concept for Cross-Sectoral Distribution Network Planning

Since the challenges of cross-sectoral distribution network planning are only being partially addressed by existing work, we describe a novel concept for a decision support system that implements the traditional planning steps of forecasting, network assessment and network optimization in a way that addresses all of the previously identified requirements. The building blocks of the conceptual system are visualized in Fig. 1 and subsequently explained in more detail.

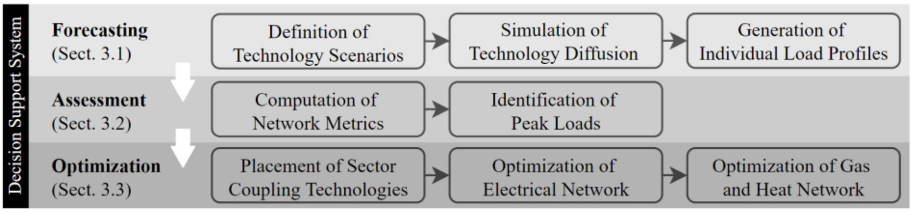

Figure 1. Overview of the proposed concept for cross-sectoral distribution network planning.

3.1 Knowledge-Driven Forecasting on Connection-Level

With respect to the long planning horizon, the creation of realistic load forecasts is crucial in achieving optimal planning results. Our suggested concept therefore employs a knowledge-driven forecasting approach that considers individual connections of end users. It consists of three building blocks:

During *"Definition of Technology Scenarios"*, decision makers formalize their assumptions about the future development of cross-sectoral technological, socio-economic, and regulatory influencing factors. The DSS guides decision makers in selecting factors and developments relevant for their use case from an extensible knowledge base and highlights inconsistencies within the defined scenarios.

During *"Simulation of Technology Diffusion"*, the effects of the network-agnostic scenarios on the end-user connections in the distribution network are computed in the form of adoption/disposal events for technologies and associated behavior, e.g., for EVs and driving profiles. Decision makers can select or specify rules that influence adoption, e.g., by initially declaring only wealthy households as eligible for EVs.

During *"Generation of Individual Load Profiles"*, hourly load profiles per end-user connection are computed by merging a standard load profile with load profiles of the assigned technologies and behavior. Demand side management is considered.

3.2 Simulation-Based Network Assessment & Worst-Case Identification

The assessment module calculates the impacts of the computed load forecasts on the distribution network and prepares the data for the subsequent optimization.

During *"Computation of Network Metrics"*, the network is evaluated with respect to the reliability and sustainability metrics using a simulation-based approach to give decision makers a first idea about the impacts of their defined scenarios on the network.

During *"Identification of Peak Loads"*, the load forecast is analyzed in fixed time intervals up to the planning horizon to determine the potential peak load the network must sustain in each interval for each end-user connection across all sectors. Existing cross-sectoral flexibility options are considered. This approach ensures the optimization adapts the network to handle the worst-case simultaneity of loads later. It furthermore decreases the runtime of the subsequent optimization.

3.3 Cross-Sectoral Energy Distribution Network Optimization

The optimization module aims to design a long-term expansion plan of the energy distribution network. The network must be adapted such that the peaks for electricity, heat, and gas calculated by the assessment module can be sustained. A particular challenge is to consider sector coupling while maintaining a calculable complexity of the problem. One way to combine different optimization approaches and conceive a cross-sectoral optimization is to design a multi-level optimization model as follows:

During *"Placement of Sector Coupling Technologies"*, an algorithm optimizes the use of cross-sectoral elements such as electric storage systems or micro combined heat and power plants where the energy of one sector feeds into another.

During *"Optimization of Electrical Network"*, the electrical distribution network is adapted to the new requirements. In contrast to traditional consumers, the elements of sector coupling can be used as flexible consumers and producers to solve transportation bottlenecks or voltage quality drops without network expansion.

During "*Optimization of Gas and Heat Network"*, the gas or heat network must be adapted, whereby the previously flexible demands of the sector coupling units have now become fixed in- and outputs due to the previous optimization results of the second stage. Gas and heat are combined here, since in a typical distribution network both do not exist at the same time.

Finally, an optimization over several time steps with fluctuating demands enables the creation of a network transformation plan to be proposed to the decision maker.

4 Contributions, Discussion & Future Work

This paper presents a concept for a decision support system that addresses the identified requirements for long-term, cross-sectoral distribution network planning (Section 2).

The knowledge base underlying the system's *forecasting* module (Section 3.1) enables decision makers to maintain an overview of all influencing factors during scenario creation, regardless of their associated sector (R1). Even though the end year of the scenarios can be arbitrarily far in the future (R2), the temporal and spatial resolution is kept high by considering hourly load profiles of all end-user connections (R3, R4).

The *assessment* module (Section 3.2) evaluates the network with respect to its individual (cross-sectoral) assets (R1, R4) and additional metrics like sustainability. The assessment furthermore enables designing the network for the worst-case loads while keeping the long planning horizon intact (R2, R3).

The *optimization* module (Section 3.3) as the third module derives a long-term and cost-efficient expansion plan in time intervals up to the planning horizon (R2, R3). The optimization considers cross-sectoral interactions (R1) in addition to the individual pre-existing network assets (R4).

In the future, we want to demonstrate the feasibility of our concept by applying our currently worked on DSS prototype in the context of our *FlexiEnergy* research project. We also want to analyze how our suggested DSS components can be decomposed further into smaller sub-components that can be assembled according to a decision maker's needs, thereby decreasing runtime and improving decision support quality.

5 Acknowledgements

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Datenschutz und Privatsphäre in smarten Stromnetzen: eine interdisziplinäre Analyse und Trends

Abstrakt. Stark zunehmende Informationsflüsse in zukünftigen Stromnetzen stellen eine Herausforderung für Datenschutz und Privatsphäre dar. Wie diesen Herausforderungen begegnet werden kann, wurde mittels Interviews und einer umfangreichen Literaturanalyse ermittelt, wobei einerseits daraus resultierende Akzeptanzprobleme und andererseits die Ausgestaltung der rechtlichen Rahmenbedingungen fokussiert wurde. Zur Bewältigung dieser kritischen Herausforderungen dient die proaktive, allgemeinverständliche Aufklärung und Information von Betroffenen, aber auch der rechtliche Rahmen muss stetig weiterentwickelt werden.

Schlüsselbegriffe: Energiewirtschaft, Datenschutz, Privatsphäre, Informationsflüsse.

1 Einleitung

Digitalisierung, Dekarbonisierung und Dezentralisierung der Stromwirtschaft stellt eine große Herausforderung für die nächsten Jahrzehnte dar. In Folge dieses Transformationsprozesses verdichten sich bestehende Informationsflüsse und es entstehen auch zusätzliche, die insbes. neue Marktrollen in bestehende Kommunikationsinfrastrukturen einbinden. In diesem Kontext gewinnen Datenschutz und Privatsphäre neue Brisanz. Aufgabe des Stromdatenrechts ist es, einen verlässlichen Rahmen für Reformen auf dem Wege zur Neugestaltung der Energieversorgung zu liefern. Auch Bedenken betroffener Verbrauchern/innen die die Akzeptanz neuer Technologien beeinträchtigen muss begegnet werden. Die wichtigen Fragen, welche Datenverarbeitungen im heutigen und künftigen Stromnetz stattfinden und welche Implikationen und Handlungsempfehlungen sich daraus ergeben, sollen im Folgenden kurz adressiert werden.

2 Methodik

Um Informationsflüsse und Datenbedarfe von heutigen und zukünftigen Stromnetzen zu identifizieren, wurden sechs semi-strukturierte Interviews mit Wissenschaftlern durchgeführt. Die Forschungsbereiche der Befragten reichten von der Regelungstechnik bis hin zur Erstellung von Servicekonzepten. Um relevante Literatur mit Fokus auf sensible Daten in Energienetzen zu finden, wurde eine systematische Literaturrecherche nach [1-4] durchgeführt. Demnach wurde eine Keyword-basierte Datenbanksuche, sowie eine anschließende Vorwärts- und Rückwärtssuche und eine Google Scholar Ähnlichkeitssuche vorgenommen. Hierfür wurde eine Kombination aus IS Datenbanken (AISeL) und multidisziplinären Datenbanken (Science Direct) verwendet, um einen größeren Forschungsbereich abdecken zu können. Die Datenbanksuche wurde mit den Keywords: Data Protection Regulation, GDPR, Smart Meter, Energy Sector, Privacy, sowie Energy Management durchgeführt, welche zusätzlich mit den Bolean Operatoren verbunden wurden. In den vier Datenbanken, AISeL, Science Direct, ACM und Springer Link wurden insgesamt 160 relevante Artikel identifiziert. Nach einer Durchsicht der Titel und Abstrakts kamen 73 Artikel in die Vorauswahl. Nach der Untersuchung des Volltextes auf seine Relevanz im hiesigen Kontext wurden 36 Artikel ausgewählt. Anschließend wurde mit den ausgewählten Artikeln eine Vorwärts- und Rückwärtssuche vorgenommen, wodurch weitere 5 Artikel eingeschlossen werden konnten. Bei der Rückwärtssuche wurden die Literaturverzeichnisse der zuvor ausgewählten Artikel auf weitere relevante Artikel durchsucht, welche den Pool an identifizierter Literatur bereichern könnte. Bei der Vorwärtssuche wurden Artikel identifiziert, welche die zuvor ausgewählten Artikel selber zitieren [1, 2]. Anschließend wurde eine Google Scholar Ähnlichkeitssuche durchgeführt. Final wurden 42 relevante Artikel gefunden.

Neben der Recherche relevanter Literatur, wurden insgesamt sechs Befragungen von Wissenschaftlern durchgeführt, um Informations- und Datenflüsse im deutschen Energienetz zu ermitteln. Die Befragten arbeiten in den Bereichen elektrische Energieversorgung, Energie- und Wirtschaftsinformatik, Energierecht, sowie vernetzte Energiesysteme, Hochspannungstechnik und Energiesysteme. Im Detail reichen die Fachgebiete der Experten vom Gesamtsystem im Übertragungsnetz bis hin zu Prosumern und Vermarktungsplattformen. Vor Durchführung der Interviews wurde ein Interviewleitfaden erstellt, um die Ergebnisse und erhaltenen Informationen effizient und einheitlich auswerten zu können. Die Interviews wurden von Mai bis Juli des Jahres 2020 virtuell durchgeführt und dauerten jeweils ungefähr eine Stunde. Die Befragung fokussierte hauptsächlich die Erhebung, Verarbeitung und die Übermittlung von Daten im jeweiligen Bereich des Energienetzes.

2 Ergebnisse und erste Erkenntnisse

Die im Rahmen der Interviews ermittelten Informationsflüsse sind in Abb. 1 dargestellt. Die benötigten Daten lassen sich je nach gerade betrachtetem Aspekt in verschiedene Kategorien einordnen.

Zentral ist zunächst die Unterscheidung zwischen personenbezogenen Daten und solchen, die keinen Personenbezug aufweisen. Personenbezug liegt vereinfacht dann vor, wenn die Daten sich auf eine identifizierte oder identifizierbare natürliche Person beziehen, s. Art. 4 Abs. 1 Nr. 1 DSGVO, wobei die Abgrenzung im Einzelnen umstritten ist [5]. Personenbezogene Daten sind insbes. bei Privathaushalten, die Strom

oder Systemdienstleistungen anbieten, sowie solchen mit Einspeiseanlagen oder steuerbaren Verbrauchseinrichtungen, relevant.
Daneben lässt sich auch nach Relevanz der Daten im Hinblick auf die Netzsicherheit unterscheiden. So gibt es Daten mit Relevanz für den Netzzustand, die eines anderen Schutzes bedürfen, als solche die darüber keinen Aufschluss geben [6]. Auch hier lässt sich in beiden Fällen wiederum jeweils eine Unterkategorisierung in personenbezogene Daten und solche ohne Personenbezug vornehmen.
Ferner lässt sich nach der Person differenzieren, die die jeweiligen Daten benötigt. Hier ist zunächst der Netzbetreiber zu nennen, dessen Datenbedarf sich durch zunehmend dezentrale Einspeisung künftig vermehrt auf – ggf. aggregierte – Einspeisedaten von kleinen, teilweise von Einzelhaushalten betriebenen, Anlagen erstrecken wird. Zudem werden Netzbetreiber zunehmend Daten benötigen, die den Netzzustand betreffen, und zwar in steigender zeitlicher Auflösung, ggf. sogar in Echtzeit. Weitere Neuerungen ergeben sich durch potentielle neue Marktteilnehmer, insbes. sog. Energiemanager oder Aggregatoren, s. Abbildung 1. Letztere zeichnen sich mit Blick auf ihre Datenverarbeitung dadurch aus, dass sie einerseits selbst große Mengen personenbezogener Daten der von ihnen verwalteten Haushalte verarbeiten. Andererseits führt ihre Tätigkeit aber auch dazu, dass insbes. ein Netzbetreiber, die von Aggregatoren zentral verwalteten Anlagen als eine Einheit betrachten kann, wodurch sich sein Bedarf an personenbezogenen Daten verringert [7, 8].

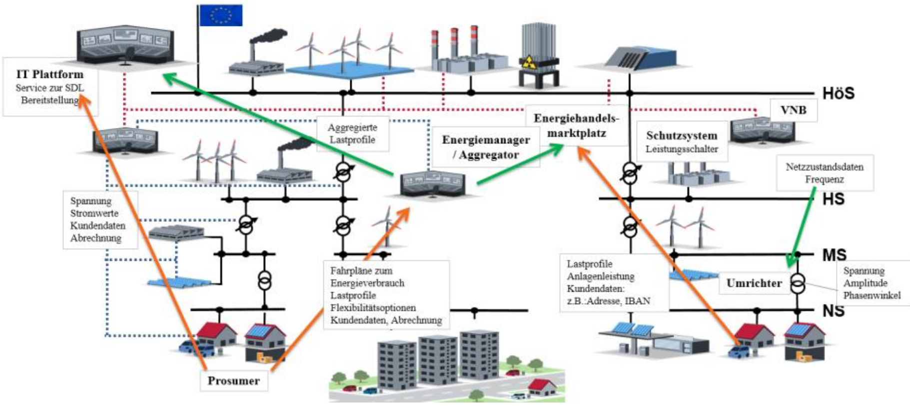

Abbildung 1: Informationsflüsse und Datenbedarfe im Stromsystem

3 Diskussion und Implikationen

Durch die zunehmenden Informationsflüsse und Datenbedarfe sowie die Partizipation neuer Akteure am Strommarkt erhöhen sich auch die Akzeptanzbarrieren bei Konsumenten [9]. Gemessene Stromwerte, können Gewohnheiten aufdecken, Nutzerprofile ermöglichen und somit die Privatsphäre der Bewohner verletzen. Basierend auf kontinuierlichen Messwerten kann ermittelt werden, zu welchen Tageszeiten die Bewohner aufstehen, kochen, schlafen, duschen, Wäsche waschen, ob jemand zuhause ist oder im Urlaub und wie der Status der Erwerbstätigkeit ist [10-12].

Weitere weit verbreitete Bedenken sind mit der Weitergabe und dem Verkauf von Daten an dritte Parteien verbunden. Skepsis erwecken außerdem mögliche versicherungswirtschaftliche Zugriffe und unternehmerische Profitinteressen, insbes. in Form von auf den Daten basierter personalisierter Werbung [12-14]. Bedenken von Verbrauchern erstrecken sich auch auf staatliche Überwachungs- und Verfolgungsmaßnahmen sowie die unerwünschte Ermittlungstätigkeit von Versicherungen im Schadensfall mithilfe intelligenter Haushaltsgeräte [15]. Sodann besteht Besorgnis im Hinblick auf Cyberangriffe, wie zum Beispiel das Abhören, und die Manipulation von Smart Metern, z.B. mit der Folge erhöhter Stromrechnungen, und nicht autorisierte Zugriffskontrollen, da solche Vorkommnisse große materielle und immaterielle Schäden anrichten können [16-19].

Auch in rechtlicher Hinsicht ergeben sich durch den erhöhten Datenbedarf neue Problemfelder. Grundsätzlich ist die Verarbeitung von personenbezogenen Daten in der EU-DSGVO geregelt, auf nationaler Ebene wird die Datenverarbeitung im energiewirtschaftlichen Kontext insbes. durch das Messstellenbetriebsgesetz (MsbG) geregelt, das unter anderem detaillierte Vorgaben dazu macht, wer welche Daten zu welchen Zwecken verarbeiten darf. Flankiert werden diese Regelungen von weiteren punktuellen europarechtlichen Vorgaben, z.B. von Art. 23 RL 2019/944/EU (EU-Elektrizitätsbinnenmarktrichtlinie).

Personenbezogene Daten können von Netzbetreibern zunächst nach den Vorschriften der DSGVO erhoben werden. Für Netzbetreiber kommen hier insbesondere die Erlaubnistatbestände des Art. 6 Abs. 1 lit. c bzw. e DSGVO in Betracht [15]. Diese ermöglichen die Datenverarbeitung zur Erfüllung rechtlicher Pflichten bzw. zur Wahrnehmung einer Aufgabe, die im öffentlichen Interesse liegt. Netzbetreiber unterliegen insbesondere nach §§ 11-14 EnWG der Pflicht, ein sicheres und zuverlässiges Netz zu betreiben, so dass eine Datenverarbeitung zu diesem Zweck in den von Art. 6 Abs. 1 lit. c bzw. e DSGVO fällt. Der Datenverarbeitung in diesem Kontext sind jedoch dadurch enge Grenzen gesetzt, dass Art. 6 Abs. 1 lit. c und e DSGVO eine Datenverarbeitung jeweils nur in dem Rahmen gestattet, der zur jeweiligen Aufgabe auch erforderlich ist. Darüber hinausgehende personenbezogene Daten dürfen hiernach nicht verarbeitet werden. Allerdings ist auch eine Datenverarbeitung aufgrund einer individuellen Einwilligung nach Art. 6 Abs. 1 lit. a DSGVO möglich [20]. Die Datenverarbeitung aufgrund einer Einwilligung birgt allerdings das Risiko, dass Betroffene die Einwilligung jederzeit widerrufen können, woraufhin die Datenverarbeitung einzustellen ist, s. Art. 7 Abs. 3 S. 1, 2 DSGVO. Mit dieser Problematik sehen sich auch neue Marktrollen konfrontiert bei denen zudem - anders als bei Netzbetreiber - durchaus fraglich ist, ob die Ermächtigungsgründe der rechtlichen Verpflichtung bzw. des öffentlichen Interesses für die Verarbeitung personenbezogener Daten einschlägig sind. Dennoch ist auch diesen Rollen eine zuverlässige, längerfristige Datenverarbeitung nicht gänzlich verwehrt: Nach Art. 6 Abs. 1 lit. b DSGVO dürfen sie - wie auch alle anderen - jedenfalls diejenigen personenbezogenen Daten verarbeiten, die zur Erfüllung eines Vertrags mit dem jeweils Betroffenen erforderlich sind.

Auch national-rechtlich ist die Verarbeitung personenbezogener Daten nur den in § 49 Abs. 2 MsbG genannten Stellen gestattet. Zu den grundsätzlich zur Datenverarbeitung berechtigten Stellen gehören nach § 49 Abs. 2 Nr. 2 MsbG die Netzbetreiber. Mit Blick auf ihren steigenden Datenbedarf gilt zunächst, dass die Erhebung und Übermittlung von sog. Netzzustandsdaten, anders als bei sonstigen sog. Messwerten, nicht auf bestimmte zeitliche Intervalle beschränkt ist. Die Verarbeitung kann jederzeit und in der Frequenz erfolgen, die für die Aufgabenerfüllung des Netzbetreibers zwingend erforderlich ist, s. § 64 MsbG bzw. § 60 Abs. 1 MsbG, und zwar auch, wenn sich diese Frequenz mit zunehmend dezentraler Einspeisung erhöht. Soweit die Messwerte einem intelligenten Messsystem entstammen, hat die Übermittlung an den Netzbetreiber auch automatisiert zu erfolgen, s. § 64 Abs. 1 MsbG. Grenzen der Verarbeitung von Netzzustandsdaten setzt die Regelung des § 56 Abs. 1 MsbG, der eine Erhebung nur in drei Fällen gestattet, wenn personenbezogene Daten betroffen sind: an EEG oder KWKG geförderten Anlagen, an unterbrechbaren Verbrauchseinrichtungen in Niederspannung oder an Zählpunkten mit Jahresstromverbrauch über 20.000 kWh. Zudem dürfen Netzzustandsdaten - ebenso wie personenbezogene Daten - nur zwischen Teilnehmern der Smart-Metering-Public-Key-Infrastruktur des BSI kommuniziert werden, um ihrer besonderen Sensibilität im Hinblick auf den Schutz kritischer Infrastruktur gerecht zu werden, § 52 Abs. 4 MsbG [6]. Weiteren Schutz erfahren Netzzustandsdaten dadurch, dass sie ausschließlich zwischen Netzbetreiber und Messstellenbetreiber kommuniziert werden dürfen, s. §§ 56 Abs. 1, 64 Abs. 1 MsbG.

Daten ohne Personenbezug können nach den Regelungen das MsbG grundsätzlich von allen Stellen verarbeitet werden. Zu den nach § 49 MsbG jedoch nicht zur Verarbeitung personenbezogener Daten berechtigten Stellen gehören insbesondere neue Marktrollen wie Aggregatoren und Energiemanager. Allerdings sieht die EU-Elektrizitätsbinnenmarktrichtlinie vor, dass die Mitgliedstaaten einen Rechtsrahmen zu schaffen haben, unter dem jedenfalls Laststeuerungsaggregatoren leichten Zugang zu Daten erhalten, s. Art. 17 Abs. 3 lit. c. Die Umsetzung dieser Richtlinie sollte bis zum 31.12.2020 erfolgen, s. Art. 71 Abs. 1. Nicht von dieser Vorgabe erfasst sind Energiemanager. Ebenso ist es unklar, ob auch erzeugungssteuernde Aggregatoren über diese Regelung Rechte zur Datenverarbeitung erhalten sollen. Sie dürfen gegenwärtig personenbezogene Daten allenfalls nach den Vorgaben der DSGVO verarbeiten, was jedoch mit den oben genannten Problematiken einhergeht.

Die Verarbeitung von Daten ohne Personenbezug, die auch keine Netzzustandsdaten sind, unterliegt lediglich allgemeinen Beschränkungen, wie beispielsweise der Vorgabe durch §50 Abs. 1 MsbG, dass Daten, die einer modernen Messeinrichtung entstammen lediglich zu den dort genannte Zwecken - unter anderem der Erfüllung eines Vertrages - verarbeitet werden dürfen.

4 Handlungsempfehlungen

Schwierigkeiten bei der Akzeptanz neuer Technologien kann durch umfassende und proaktive Aufklärung der Endkunden begegnet werden. Dazu gehören neben klaren, allgemeinverständlichen Informationen über die verarbeiteten Daten auch Hinweise zu Möglichkeiten des Rechtsschutzes, Grenzen der Datenverarbeitung und Maßnahmen zur Verhinderung des Missbrauchs von Daten. Datenverarbeitende Marktakteure, wie auch neue Marktrollen, müssen rechtliche Entwicklungen genau verfolgen und Eigeninitiative durch stetige Selbstkontrolle, Dateninventur, s. Art. 17 Abs. 1, Art. 18 Abs. 1 DSGVO, Datensparsamkeit, s. Art. 5 Abs. 1 lit.c DSGVO, und eine vollständige Transparenz bezüglich ihrer Datenverarbeitung zeigen. Der Rechtsrahmen für die Datenverarbeitung durch Netzbetreiber ist schon jetzt auch auf wachsende Datenbedarfe ausgerichtet. Für Laststeuerungsaggregatoren dagegen bleibt die konkrete Ausgestaltung der Umsetzung der EU Elektrizitätsbinnenmarktrichtlinie abzuwarten. Energiemanager und sonstige Aggregatoren müssen sich weiterhin nach den – nicht mit Blick auf die Besonderheiten des Energierechtes konzipierten – Vorgaben der DSGVO richten und gegebenenfalls ein besonderes Augenmerk darauf richten, dass ihre Datenverarbeitungen auch tatsächlich zur Erfüllung des jeweiligen Vertrags erforderlich oder von einer Einwilligung gedeckt sind.

5 Fazit und Ausblick auf weitere Forschung

Zusammenfassend war in den Interviews festzustellen, dass zunehmend personenbezogene Daten von verschiedenen, auch neuen, Akteuren erhoben, verarbeitetet und übermittelt werden, wodurch datenschutzrechtliche Rahmenbedingungen neue Brisanz entwickeln und Akzeptanzprobleme in der Bevölkerung und in Unternehmen drohen. Diese Schwierigkeiten lassen sich jedoch mithilfe von Aufklärung der von Datenverarbeitung betroffenen Parteien und genauer Beobachtung rechtlicher Entwicklungen handhabbar machen. Hinsichtlich neuer Technologien, wie künstlicher Intelligenz, Big Data, Blockchain, 5G und neuer Marktrollen, wie Aggregatoren, Energiemanager, Prosumer und sonstiger Drittanbieter entstehen weiterführende Forschungsbedarfe. Neben Fragestellungen des Datenschutzes und der Privatsphäre, müssen zukünftig auch die Themen der Nachhaltigkeit, Wirtschaftlichkeit, sowie der Versorgungssicherheit und Netzstabilität behandelt werden. Weitere Forschung zu den angerissenen Thematiken soll unter anderem im Rahmen des SiNED Projekts erfolgen.

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Assumptions on a Distributed and Hierarchical Market Concept for Balancing Reserve Aggregation

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Abstract. While transmission systems have to be decoupleable in case of failures, up to now, there is no comparable procedure for controlled islanding of distribution grids. In this work, a concept for a balancing reserve market design is introduced, which would enable distribution grid operators to contract flexibility in order to operate their grids independently. Assumptions are presented on which such a market could be based and elements of it are presented. Furthermore, research gaps in order to develop such market are illustrated.

Keywords: distributed market, balancing reserve, hierarchical market, controlled islanding

1 Motivation and Introduction

In case of a transmission system blackout (TSB), distribution grids in most of Europe cannot use local flexibility to stay powered. This holds true, even though renewable energy sources (RES) and flexible resources like electric vehicles [1,2], or consumer-side batteries [3,4] are largely present at lower grid levels. Balancing reserve (BR) markets pose an additional risk because they represent single points of failure in the energy systems. They might have redundant platforms, but no (by-design) backup. Thus, they are threatened by cyber attacks.

If distribution grids are supposed to continue operating during a TSB, they would have to separate from the overlying network and create a grid island (cf. [5]). Research studies about islanding of microgrids have already been conducted for some time (e.g. [6-10]).

The following aspects constrain the role of distributed energy resources (DER) in stable distribution grid operation for islanding operation:

1. **Market barriers:**
   Small DER cannot join BR markets due to the minimum bid size [11,12]. Aggregation has been proposed to overcome this issue [13] as comprehensively defined by the Universal Smart Energy Framework (USEF) aggregator role [5], which was introduced to bring flexibility of small DERs combined to the market [14,15]. The USEF aggregator concept includes controlled islanding as a system service to the distribution system operator (DSO) [5]. However, its implementation has not been defined.

2. **Neglect of distribution grid requirements by the BR system:**
   Since at least the harmonization of the European BR system [16-19],[1] BR markets allocate resources only according to their locality in relation to the load frequency control (LFC) areas or blocks.[2] The transmission system operators (TSO) have to be able to operate LFC areas or blocks independently[3] and decouple their systems in case of technical problems or inconsistent market results.[4] However, while neighbored transmission systems have to be decoupleable, up to now, there is no comparable concept for controlled islanding of distribution grids.

This work presents an idea for the market design of a new distributed BR market addressing these issues in line with the current BR systems and the EU directive on common rules for the internal market for electricity [20] with a focus on the assumptions underlying its concept. Our approach aims to increase flexibility procurement from DERs for the transmission as well as the distribution grid, which is compatible with necessary islanding.

The rest of this work is structured as follows: First, we give an overview on market based approaches for system stability in the field of distributed / hierarchical approaches (Section 2). Afterwards, we present the underlying assumptions of the proposed concept (Section 3). Finally, we describe a distributed, hierarchical BR market concept (Section 4) and provide a conclusion together with a perspective on future work (Section 5).

2 On Markets for Distribution Grid Stability

If requirements of DSOs are to be respected, either the LFC area-wide BR market has to integrate DERs and consider the connected grid operator(s), or DSOs have to operate their own markets. An integration of all DERs into a single system-wide market is prohibitively costly. Therefore, a DSO-sided market is considered in this work with a hierarchical link to the LFC area-wide BR market to offer flexibility of DERs for the transmission system as well.

Studies on markets concerning DER flexibility for the distribution grid have already been conducted. Hierarchical markets which can control a large number of DERs were for example the PowerMatcher [21] and DEZENT concept [22]. Both perform market operations in real-time with manageable calculation effort and consider line constraints. Within the PowerMatcher, this is realized with demand-price function of every DER. Based on this, a “tree structure” [21] of agents determines a market equilibrium by locational marginal pricing. Within DEZENT [22] decentralized agents trade energy by real-time negotiations in a static bottom-up approach, while unstable grid states are detected and solved by the activation of so-called “conditioned agents”. However, in both approaches, computational intelligence would have to be introduced into every

[1] https://www.entsoe.eu/network_codes/eb/imbalance-netting/ [Accessed 28 November 2020]
[2] https://www.regelleistung.net/apps/datacenter/tenders/ [Accessed 28 November 2020]
[3] Electricity Balancing Guideline (EU) 2017/2195, Reason (10) [16]
[4] https://www.regelleistung.net/ext/static/prl [Accessed 28 November 2020]

grid connection point to calculate the required operations. Furthermore, they lack regulatory compliance.

Decentralized ancillary service markets for the DSO were also developed within the German c/sells project [23]. They run on regional platforms of the respective DSO and are used to ease grid congestions. Owners of DERs can place flexibility offers at the market and the DSO performs an optimization, how to operate its grid most cost efficient. One shortcoming of this markets is, that they are each run on a central platform within the distribution grid and in this way constitute a single point of failure. The architecture does not comprise a distribution concept.

In the Smart Nord project [24], locational information is attached to offers at the central energy exchange. Grid operators can purchase them and thus ease grid congestions or relieve overloaded transformers. However, this work does not focus on BR and does not include a distribution concept either.

3 Proposed Approach and Assumptions

In distinction to the previously presented works, we recommend a distributed market to aggregate BR for the distribution grid. Before it can be developed properly, some assumptions are crucial regarding the current and future BR system. They have to be discussed and agreed upon, because the conceptualized market design relies on them:

1. **Stable operation of distribution grids in islanding mode is depending on DERs:** The flexibility of DERs is needed to keep distribution grids online during a potential TSB. During normal operation, distribution grids rely on the connection to the transmission grid, and DSOs do not have enough own equipment to stabilize their grids by themselves.
2. **It is economically efficient to provide flexibility by DERs to keep the transmission system stable in the future:** The utilization of flexibility from lower grid levels is less expensive than running additional capacities only for stabilization purposes. Therefore, in case of large shares of renewable energy sources, it makes sense to integrate them into the LFC area-wide BR market.
3. **A hierarchical (not distributed) market on distribution grid level will be subject to cyber attacks:** DSOs have fewer resources at their disposal than TSOs to defend their server systems. Thus, they cannot afford to setup appropriate security measures, which makes by-design security crucial for a BR system at distribution grid level.
4. **Reliable traceability of provided balancing reserve is given for DERs.**
5. **It is technically feasible to separate distribution grids from transmission grids:** Installed control and protection technology at transformer stations can cope with the electro-magnetic phenomena that occur, when distribution grids are separated from a potentially already failing transmission grid.
6. **In case of a failing transmission system, digital communication is still possible between the distribution grid operator and DERs:** Information about when to stabilize the distribution grid, and about further market operations can still be exchanged. It is either realized by using UPS/batteries at the relevant ICT nodes, or by a step-wise ICT restart powered by the islanded distribution grid (e.g. [25]).

4 Concept of a Distributed Balancing Reserve Market

In order to overcome the issues from the motivation and shortcomings of previously published approaches, a distributed BR market for every distribution grid is proposed. Its key characteristics are the following:

1. The distributed market is situated at the distribution grid, which creates a hierarchical BR market architecture by constituting a second market level below the LFC area-wide BR market. The distributed approach removes the need for a central server structure and thus reduces vulnerability to cyber attacks and lowers the realizable minimum bid size.
2. At the distributed market, agents would exchange flexibility offers with dedicated prices and in this way aggregate balancing reserve capacity. In a distributed market, all agents would be equal to perform market operations and aggregate BR products.
3. The aggregated BR is supposed to be compatible with both the LFC area-wide and the distributed market. This way, aggregated BR can be brought to the transmission system level market and is at the DSO's disposal in case of a TSB as well. The DSO can use the same mechanism to acquire additional BR capacity, for which approaches to determine the necessary BR amount can be derived from [26] or [27].

A meaningful market mechanism is still to be evaluated. Meaningful market operations from literature are auctions and negotiations [28]. Due to less market participants a market clearing with more sophisticated products than a simple merit-order would be possible in reasonable calculation time. This might compensate for lower liquidity at the distribution grid market. Here, a market engineering approach could be pursued (e.g. [29-30]) in combination with a game theoretic market model.

At the distributed market, it is important that unequally large DERs do not enable participants to gain excessive market power. At the same time, the distributed market operations must not be exploitable by the distributed participants. A promising method to examine this issue seems to be a game theoretic analysis in combination with agent-based computational economics (e.g. [31]).

5 Conclusion and Future Work

In this work, we motivated the need for a hierarchical BR market design with distributed market operation at the distribution grid level. By this means, more flexibility of DERs could be brought to the BR market. At the same time, distribution grid islanding based on a distributed system would supplement the current harmonized European BR system with a security by-design element.

We presented assumptions, on which the development of such a market can be based. The uniform market design allows an application for the LFC area and the distribution grid level by the same mechanism. Future work will include the selection of proper market operations and an evaluation on how an exploitation of the distributed market by the participants can be prevented.

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Development of Scenarios for Modelling of Districts' Energy Supply and Analysis of Interdependencies between Energy and ICT

Abstract. The increasing digital transformation in energy supply systems allows greater control and possibilities for performance optimization and efficiency. This is accompanied by increasing complexity of the system, and thus requires the evaluation of interactions between energy and information and communication technologies (ICT) involved. One of the goals of the project "Zukunftslabor Energie" (Future Laboratory "Digitalization Energy") is to analyze these interactions in highly integrated digitalized systems for district energy supply. For this, simulation studies must be conducted to configure flexibilities. A first step is to define appropriate analysis scenarios. Requirements for these scenarios, the related models, and one of the considered scenarios are described in this paper. This allows to discuss the system, its boundaries, its components, and their interactions. Future research requires an analysis and discussion of requirement specifications, data collection and treatment, model construction, model implementation, and model validation.

Keywords: Energy Supply Scenarios, District Energy Supply, Smart-Grids, Digital Transformation of Energy Systems.

1 Introduction

The role of digital transformation in energy supply systems has become increasingly important, as it enables the acquisition, monitoring, communication, analysis, and optimization of relevant measured values, and the (remote) control of (decentralized) energy conversion plants and operating equipment. This allows a more efficient operational management, which adapts to the rapidly changing processes of energy economics. A complex integrated energy system, which includes different energy supply and conversion forms such as electricity, heat, or gas, creates on one hand a different kind of flexibility, that allows, for example, a quick and accurate reaction to forecast uncertainties of fluctuating decentralized energy supply. On the other hand, it drastically increases the system complexity, which affects modelling and control in several fields like cost-effectiveness, financial viability, flexibility, technology acceptance, data security, and usability [1].

The aim of the Project "*Zukunftslabor Energie*"[1] is the investigation of interactions in highly integrated ICT- and energy systems for district energy supply (objective 1), and the parallel development of a platform that enables networking of researchers and stakeholders (objective 2) to facilitate the transfer of innovative research results and support further investigations, focusing on the above-mentioned fields in digitalized energy systems.

The topic of this paper refers to the first of five main work-packages within the first objective of the project ZLE, with the central target of research and development of digitalized energy systems. To describe a comprehensive framework of such energy systems, highly integrated application scenarios for three sample districts in Germany are to be defined and thoroughly analyzed. Each scenario represents an objective towards an energy system which is, when compared to a baseline, possibly more efficient, sustainable, economical, securely protected against cyber-attacks, and accepted by stakeholders. Despite of the importance of field and laboratory tests, computer simulations and numerical optimization processes play a major role in the project due to configuration flexibilities and saving of considerable development costs. This reflects the need for conducting simulation studies to analyze the different scenarios.

The first work-package deals with the identification and definition of relevant energy supply scenarios in districts and use cases for the investigation of ICT dependencies. Subsequent work-packages cover the identification and assessment of requirements of relevant models for the simulation and analysis of the defined scenarios, modelling and development of the integrated supply scenarios, systematic experiments, tests and analysis, and finally, processing and publishing of the results. The goal is to develop a modelling framework that includes the demand for heating, transport, and electricity, and considers the trade-offs between energy supply and ICT systems.

This paper focuses on presenting the process of scenario definition. Section 1 provides a short overview of the project research activities. Section 2 summarizes information on modelling of smart energy systems. Section 3 describes the requirements of the energy scenarios for residential districts. Section 4 gives an example and an overview of a scenario to be modelled, and details the components considered for those scenarios and which elements are included. Conclusions in Section 5 are oriented to the next steps of research activities.

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[1] zdin.de/zukunftslabore. Last visited on 28/01/2021.

2 Modelling Smart Energy Systems for Districts

The overall motivation when developing scenarios for district energy systems is the cost-efficient application of renewable energy sources while minimizing greenhouse emissions [2]. In the case of the districts electrical energy supply, decreasing costs for photovoltaic systems and declining feed-in tariffs are turning the self-consumption of the photovoltaic electricity lucrative [3]. Such a decentralized expansion of renewable energy sources could also be economically favorable due to lower grid expansion costs than in the centralized cases [10]. In addition, the storage of electrical energy has become more attractive due to subsidies and decreasing costs of battery storage systems [4]. Combinations with electrolyzers indicate a promising attempt to process all the produced renewable energy. Heat supplied through heat pumps is also gaining importance in new buildings or newly build districts [3]. Moreover, districts' low voltage grids face new challenges due to the increasing adoption of electric vehicles and charging processes taking place in households [5].

The integration of ICT systems in the energy system allows a more flexible operation and facilitates the coupling of renewable energy sources [6]. The ICTs enable an energy management system which supports the control functions needed to regulate energy flows and to participate in energy trading markets [7]. ICT systems in the energy sector relate to all applications which simulate a district as a spatial framework and the district's energy system behavior. The goals of such a system are: to study and control the application of energy strategies and measures; to monitor energy generation, supply, transmission, and consumption; or to manage the demand side. This aims to improve the energy system performance [8]. The analysis and optimization of ICT solutions are gaining importance in the energy sector due to the fast transformations of energy systems [9]. Smart grids allow communication for efficient management and resource control, and micro grids are designed to effectively integrate local distribution and generation, and to operate in both non-autonomous (grid-connected) and autonomous (stand-alone) modes [10]. Several studies review different ICT and network infrastructures for micro grid operation and control [11]. Flexibility of implementation, installation costs, efficiency of communication range, security, availability, and scalability belong to the most important considerations for implementing the ICT layer. Several alternatives for communication and control methods offer higher flexibility and reliability. As an example, a multi-agent system decentralized approach considering long term optimization to solve the scheduling of distributed energy resources is presented in [12].

The combined simulation of energy systems and communication networks has attracted attention due to rising interest in smart grid from governments, industry and academia [13]. Parts of large systems are typically modelled and simulated by different techniques and tools [14]. A combined simulation of energy systems and ICT infrastructure can be achieved using a co-simulation [13]. Co-simulations allow the consideration of interdisciplinary dynamic interactions of complex components and systems. They couple independent simulation tools representing different parts of the system [15]. The objective is to develop a model which is able to share inputs among various simulation tools and link outputs to the inputs of a second tool [16].

Individual simulators are independent black boxes that need an orchestrator to couple them. It controls how the simulated time progresses in each simulator and moves data from outputs to inputs according to a scenario [14]. In the context of smart grid co-simulation, a co-simulator would consist of a specialized communication network simulator (e.g. OMNeT++) and a specialized power system simulator (e.g. OpenDSS, pandapower). An example of such an orchestrator is Mosaik[2], a modular smart grid simulation framework supporting automatic composition of existing, heterogeneous simulation models for the evaluation of control strategies for heterogeneous distributed energy resources and loads [13]. Setting up a co-simulation requires therefore the definition of the objectives and the preparation of scenarios [17].

3 Requirements of the Energy Scenarios for Residential Districts

3.1 Modelling objectives

One of the objectives of the is the study of interactions in highly integrated energy and ICT systems in districts. Interconnections between the electricity sector and heat, power, or gas sector increase the system flexibility. The integration of renewable energy sources introduces new challenges to the distribution grid [18].

The central technical research question is the identification and modelling of complex interactions between ICT and energy systems. This is to be achieved through identification and modelling of complex interactions between ICT and energy systems, and the investigation of (cyber-)resilience in districts. The influence of electrical measurements, monitoring and automation systems on the efficiency, optimality, and stability of (decentralized) energy supply concepts, including technology acceptance, is to be specifically investigated. This shall include dynamic scenarios with temporary reduced availability of ICT systems, either due to capacity utilization, technical failures, or systematic attacks. The ICT systems allow a flexible operation of the facilities that enables optimization of parameters such as cost, self-consumption, or greenhouse gas (GHG) emissions. The different technological components are to be integrated in simulations to evaluate their interactions.

The simulations require an application-oriented approach. Scenarios aim to investigate the influence of monitoring technologies on the efficiency and stability of the system, autonomous power optimization, energy optimization, and marketing of flexibilities to third parties.

3.2 Model requirements

The simulations require models representing real systems from selected residential districts [19]. It is first required to define what is going to be modelled and how this could be achieved, independently of the used software [20]. This should define the

[2] https://mosaik.offis.de/. Last visited on 28/01/2021.

model boundaries, the components, their activities, relations, and resources, as well as inputs and outputs [21]. A bottom-up modelling approach is used. Models are built up from extensive data on energy use and energy demand [22]. Engineering models make use of physical and technological characteristics of individual components to compute their performance. These models have the highest level of flexibility in evaluating technological developments and energy efficiency scenarios [22].

A systems-wide perspective that takes into consideration the trade-offs between different components of the energy system is needed [23]. To describe an energy system in a district, the following components need to be described [24]:

a) System boundaries:

The considered systems shall encompass the energy supply and use within an energy district, from the connection points to the local energy grids, to the energy use by the residents and facilities, also including local energy supply and local energy networks, and the energy managing and monitoring systems for the energy supply and use. Centralized external energy generation coupled to the energy system is also considered.

b) Components:

To investigate the interactions between ICT and energy systems, the following components are to be considered:

- Energy grids, such as electrical or gas grids.
- District energy supply outside of the residential district (sector coupling).
- District distribution grids, energy supply and storage.
- Buildings distribution grids, energy supply, and storage.
- Final users, including their energy demand for heating, cooling, electricity and transport [23].
- External data sources and energy markets.
- Centralized and decentralized Energy Management Systems (EMS), including monitoring, controlling and supervision devices.

c) Interactions

The flows of energy and data between the components need to be considered. This allows evaluating energy transport, transformations, losses, and final energy use. The data flows for monitoring and controlling of the system by the Energy Managing Systems (EMS) allow the evaluation of the interactions between the ICT and the energy systems.

d) Inputs and outputs

These relations between data and energy flows allow to evaluate the behavioral dependencies between the energy and the ICT systems, and the impact of the different scenarios on performance metrics. This requires a data input that considers meteorological conditions, component physical properties, energy demand time-series, and development of scenarios for different cases of ICT performance. Occupants demographic profiles allow assessing energy demand profiles and studying technology acceptance for both energy supply and ICT components.

4 Scenario Overview

This section presents an exemplary scenario of an energy supply system in a district, which will be modeled within the research activities of the project. The underlying district called "Rüsdorfer Kamp" belongs to the city of Heide in the district of Dithmarschen, Schleswig-Holstein, the northernmost state of Germany. The concept of the district energy supply system was developed by the Steinbeis-Innovationszentrum energie+ (siz energie+)[3] during the research project QUARREE100[4]. Responsible for the overall project coordination are the Development Agency Region Heide[5] and the Advanced Energy Systems Institute[6]. The project runs from 2018 to 2022. QUARRE100 focuses on the conversion, storage, control, and distribution of renewable energies in the urban district "Rüsdorfer Kamp". This urban district is considered due to its representative building stock and its mixed-use – private and commercial – which allows a good transferability to other urban districts. Specific requirements for the energy supply system the research project QUARREE100 are, among others:

- **Renewable energies and GHG emissions**: Fully utilize electricity from renewable sources, through the complete integration of renewables, for example, by considering central and decentralized renewable energy sources. Complete avoidance of GHG emissions in the neighborhood in the long term.
- **Resilience and responsiveness**: In case of failures of one or more subsystems of the energy supply system, the remaining system should compensate the failures quickly and flexibly.
- **System usability**: Contribute to the overall goal of making the energy system more flexible. In accordance, the district energy system should provide grid support. This will be achieved by providing an intelligent energy control system in the district.
- **Future mobility**: Another goal is to create interfaces for sustainable mobility using different energy sources such as electricity and hydrogen. For this purpose, in addition to charging stations for electric vehicles, fuel dispensers for hydrogen-based fuel cell drives are to be created as part of a "filling station of the future".

Figure 1 illustrates one scenario. It depicts one design of the energy supply system of the district at "Rüsdorfer Kamp". In the following, the main components of the district's energy supply system are briefly described:

- **Electrolyzer**: The electrolyzer is required to produce the hydrogen needed for the "refueling station of the future". The hydrogen produced is temporarily stored in a pressurized gas tank.

[3] Steinbeis-Innovationszentrum energie+, steinbeis.de/de.html. Last visited on 29/11/2020.
[4] QUARREE100, quarree100.de/. Last visited on 29/11/2020.
[5] Entwicklungsagentur Region Heide, region-heide.de/entwicklungsagentur/. Last visited on 29/11/2020.
[6] The Advanced Energy Systems Institute, pse.uni-bremen.de/aes.html. Last visited on 29/11/2020.

- **Heat network and heat pumps**: A separate heat network will be implemented in the district for the heat supply. It will only be temporarily connected to the public grid and is fed by several heat pumps within the district. The heat pumps will provide most of the needed heat energy in the district.
- **Thermal storage**: The thermal heat accumulator has a large capacity and seasonal storage capacity.
- **Combined heat and power (CHP) plant**: The CHP prioritizes heat before power generation and serves to provide heat during peak heat demand.
- **Electric grid**: The electric grid is to be designed as a closed district operating system. Therefore, it is decoupled from the public electric grid. In the shown scenario this is altered due to the desired consideration of flexibility marketing. The substation connecting the district grid with the public grid will consist of an adjustable local grid transformer to ensure an active voltage regulation.
- **Photovoltaic system**: The electricity production is completely designed for self-consumption, such as for the heat pumps. The district operator leases the necessary roof areas of the residential and commercial buildings in the neighborhood.
- **Battery storage system**: In addition to the storing of the produced renewable energies it serves to ensure grid stability. Accordingly, it is used for peak-shaving, voltage regulation and the provision of reactive and balancing power. It also provides energy for the heat pumps in the evening.
- **Charging infrastructure for electric vehicles (EV)**: This will be coupled with a charging management system that ensures that the EVs are mainly charged with locally generated renewable energy.

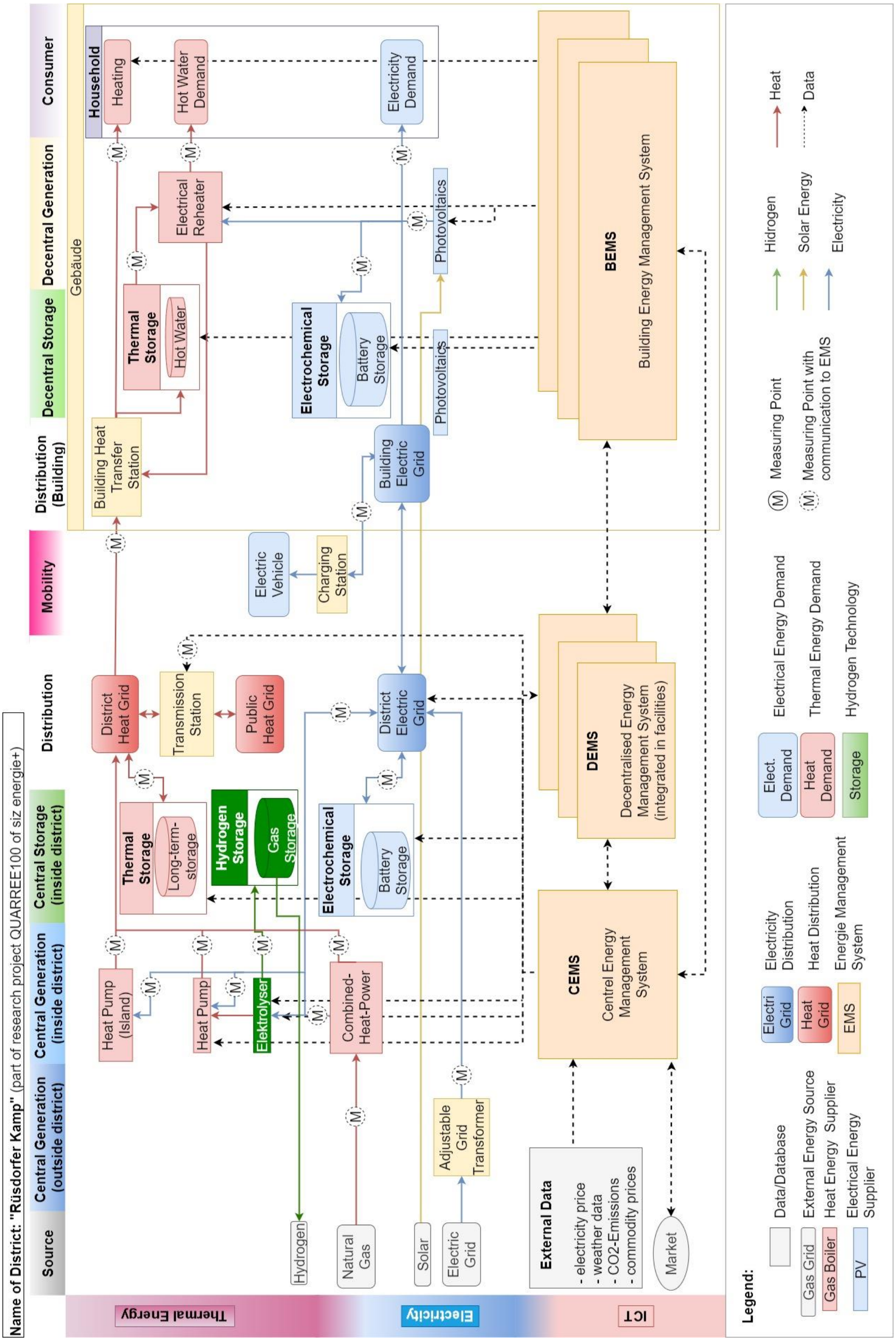

Figure 1. Schematic representation of the developed energy supply scenario for Rüsdorfer Kamp.

5 Conclusions and Future Research Agenda

This paper summarizes the research activities for the investigation of interactions between highly integrated ICT and energy systems for district energy supply. The research goal reflects the requirements of developing simulation studies for the analysis of the interdependencies of ICT end energy devices in digitalized energy systems. To achieve this goal, three residential districts are chosen, and the example scenario Rüsdorfer Kamp district is introduced. This scenario was developed starting with an analysis of the project objectives and research questions and followed by a definition of model requirements. The system boundaries, the components and their interactions are described for the presented scenario.

Future work follows the steps of simulation studies procedures [24]. For this, an analysis of the requirements and interfaces of each of the different model components is the next step to obtain requirement specifications for the models and its components and develop formal models for the scenarios. Furthermore, different types of data, including component behavior and properties, interfaces, energy demand profiles, energy markets data, device communication characteristics, are therefore required to implement and execute models that allow evaluation of these scenarios.

Additionally, to perform simulation of different components and systems, an approach of coupling different simulation tools representing different parts of the overall system is required. Co-simulation has been identified as an efficient and flexible approach that allows consideration of interdisciplinary dynamic interactions [15, 25]. This enables domain-specific components such as power grids or communication networks to be addressed by their modelling tools, to share inputs among these tools, and to link outputs to the inputs of a second tool, so different components can be integrated [16, 26].

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Transitioning to Condition-Based Maintenance on the Distribution Grid: Deriving Design Principles from a Qualitative Study

Abstract. Electric utilities, as an asset-intensive industry, are facing global trends impacting their distribution grids drastically. The mobility revolution and striving for carbon-neutral energy generation already impact the burden of aging assets, e.g., switchgear and transformers, and will stress central assets even more in the future. Condition-based maintenance stands out as a promising strategy for future asset management of the distribution grid. By interviewing different electric utilities, we identify practitioners' problems of the current situation and derive design principles enabling a joint system for data analysis and result presentation using condition-based maintenance. The resulting design principles encompass an automatic detection of upcoming maintenance activities, a holistic system integration, permanent condition monitoring, incident and knowledge documentation, and workforce management. Our qualitative approach reveals knowledge of the current situation and lays the foundation on how to overcome existing problems for the transition to condition-based maintenance on the distribution grid.
Keywords: Condition-Based Maintenance, Predictive Maintenance, Distribution Grid, Qualitative Study, Design Principles.

1 Introduction

Electric utilities are an essential part of society supplying electricity to households and industry. Therefore, they must manage the distribution grid as an asset-intensive energy delivery network. A distribution grid consists of high-voltage (HV) energy-generating power plants, power lines for energy transmission, stations for transformation to medium-voltage (MV) energy, further cables and distribution lines, substations for transformation to low-voltage (LV) energy, and finally cables to the energy consumer. The stations for energy transformations contain valuable assets, e.g., switchgear and circuit breakers, and are positioned on various places inside the whole grid area. Research pledges for development towards a smart grid [1], but especially the part of the grid beginning at the MV transmission is poorly automated and falls behind in comparison to HV transmission [2]. Currently, this field is addressed by few research articles, but so far, the focus on the design of a holistic system has not been taken into account.

As for all asset-intensive industries, maintenance is a critical activity for electric utilities. Generally, there are different strategies for maintenance [3]: Reactive maintenance, preventive maintenance, reliability-centered maintenance, and condition-based maintenance. Reactive maintenance enforces failures, as actions are only performed in cases of failure. Preventive maintenance is based on regular maintenance intervals. Reliability-centered maintenance is a risk-based strategy to focus on fast repairs in failure cases [4]. In contrast, condition-based maintenance (also called predictive maintenance) relies on condition data of the equipment to predict upcoming failures and schedule activities to prevent these failures. Thus, condition-based maintenance can drastically extend the lifespan of critical assets. Concerning the distribution grid, especially regarding substations, condition-based maintenance is not yet applied. However, there are some ideas and first approaches to how condition-based maintenance could be applied to MV components [5]. Other examples include condition monitoring and condition-based maintenance on wind turbines [6, 7].

Current trends in the energy sector further increase the pressure on aging components of the distribution grid. The ambition to focus on renewable energies combined with the energy turnaround [8] and the mobility revolution fostering electric vehicles stand out as future challenges. These trends force the distribution grid to become more decentralized and withstand higher load variations, further stressing its central components. To overcome these challenges from a managing perspective, we aim to design a system for data analysis and result presentation for condition-based maintenance on the distribution grid. In the context of this overarching design science research study, we start by qualitatively interviewing electric utilities. We identify their current situation and derive design principles as a method of capturing central requirements to a condition-based maintenance system. We focus on the overall system, neglecting the choice of machine learning algorithms for now. Instead, we contribute to the theory by showing design guidelines for condition-based maintenance systems on the distribution grid. Our insights are also highly relevant for practical use, e.g., for electric utilities.

The remainder of the paper unfolds as follows. In Section 2, we position our study in the theoretical background of energy informatics and maintenance strategies. In Section 3, we present our qualitative approach and the overall design science research process. Section 4 contains the result of our study, combining the current situation and the derived design principles. After discussing our results in Section 5, Section 6 concludes the paper and portrays prospects for future research.

2 Theoretical Background

We start with an introduction into the IS domain *energy informatics* and continue with the theoretical background on different maintenance strategies and their application on the distribution grid.

2.1 Energy Informatics

In times of temporarily increasing energy demand for electric mobility and, at the same time, higher load fluctuations in existing networks due to decentralized energy supply by renewable energies, the field of energy informatics has become increasingly important. Energy informatics is based on the precept that a combination of the energy domain and information engineering, i.e., Information Systems (IS), increases both efficiency of energy utilization and carbon-efficient energy production [9]. Thus, combining energy and information contributes to advancing environmental sustainability and has a significant impact on the transition to a renewable energy society that operates at a consistently high level of energy efficiency [9–11].

As renewable energy production is inconsistent and difficult to predict, mismatches between demand and supply can occur. The effective storage of energy, the impact of grid components on nature, and, finally, the transport of higher volumes of energy through the existing grid are current challenges the energy sector has to deal with [12]. Energy informatics is a discipline that tries to overcome these kinds of challenges by employing new, smart technologies to facilitate the network control of distribution grids, which are put into practice by a smart grid [13].

Forecasting of future grid load (electricity usage) is a major task to provide intelligence to the smart grid, plan the required resources, and take control actions to balance the supply and demand [14, 15]. The rethinking of many consumers and industrial companies in the energy sector because of climate change and the environmental debate over the last years is also affecting the field of smart grids and intelligent power components. For example, since 2010, the installation of smart electricity meters is required by law in Germany, which enables a better understanding of customer behavior by monitoring organizational and household energy consumption in real-time [10, 16]. Distribution grids are currently experiencing a transformation from passive to active networks [17]. Further developments include a user-centered information system that assists private households in making efficient energy consumption decisions, so-called microgrids, and analytical approaches for preventive maintenance in large power grids like New York City [17–20].

In the area of MV power networks, smart grids play a crucial role. Supply reliability is the essential task of energy suppliers and approaches of energy informatics are a driving force for the increasing digitization of supply grids. In this context, the prediction of the electrical load and the permanent monitoring of network components play a key role, which in turn significantly influences the energy supply and the way energy suppliers operate.

2.2 Maintenance Strategies

Maintenance as a domain of checking and repairing assets has seen strategic modifications in the last years. It began with visual inspections, which are still used today [21], and changed to four different strategies for maintenance: reactive maintenance, preventive maintenance, and condition-based maintenance [3]. Reactive maintenance describes a strategy of operating assets until a malfunction or defect occurs and then repairing the equipment. By definition, this maintenance strategy neglects planned or scheduled inspections and opts for using components for the maximum duration, while costs for spare parts are minimized [3]. However, reactive maintenance not only tolerates downtimes but enforces them.

Preventive maintenance utilizes intervals based on e.g. operating hours, experience, or distances (cars, airplanes) for scheduled maintenance of assets and equipment to prevent malfunctions and defects [3]. Components will be replaced once they pass defined thresholds, which prevents downtimes but might provoke replacements before the possible lifetime is reached [3]. Concerning costs for spare parts and assets, preventive maintenance is more expensive than reactive maintenance [3]. Reliability-centered maintenance, as another popular maintenance strategy, is focused on ensuring continuously operating machinery by assessing risks of failure cases [4].

Condition-based maintenance [22], also called predictive maintenance, is the most advanced maintenance strategy. It relies on sensors detecting condition changes and failures and advanced signal processing techniques based on pattern recognition [23]. Condition-based maintenance reduces or even avoids downtimes because maintenance activities are scheduled just when a defect will occur [3]. This follows the assumption that in most cases, equipment failures will not occur after a fixed amount of time in service but can occur at any time, sometimes randomly [23]. Thus, the current condition of an asset (mostly accessed via supervisory control and data acquisition (SCADA) systems) has to be considered, including data from other information systems used in the businesses, especially enterprise resource planning systems (ERP) [24]. Integrating ERP systems to the condition-based maintenance processes can also be helpful because ERP systems—in most cases—provide standardized processes and data supporting maintenance activities. Combined, businesses applying condition-based maintenance as a maintenance strategy benefit from unnecessary equipment replacement, improved safety and efficiency, and save costs by optimized availability [23]. An example of condition-based maintenance in use is nuclear power plants. Nuclear power plants are condition-based highly advanced industry equipped with different sensors, instruments, and analytical methods to extend the time-to-failure [21]. Because they cannot afford the risk of severe failures condition-based maintenance offers the best consideration between safety, costs, and uptime. Current research on condition-based maintenance is focused on industrial production and manufacturing, including the algorithms and data necessary [25, 26]. From another point, the hype of machine learning and AI can be traced to condition-based maintenance, as this maintenance strategy is the leading use case for machine learning and AI in the industry [27, 28].

Adding advanced aspects of condition monitoring [22] and condition-based maintenance is one of the features necessary to classify the distribution grid as a smart grid [2]. However, other criteria have to be fulfilled as well, such as self-automation and smart meters [2]. Therefore, we refrain from using the term *smart grid* and stick to *distribution grid* as we exclude other factors and focus on condition-based maintenance.

There are different approaches to apply condition-based maintenance to the distribution grid, most including predictive models for specific equipment or machinery. Examples are a cloud-driven condition-based maintenance model for wind turbines [7] and different factors impacting the reliability of transformers with condition-based maintenance methods to identify these factors and derive required maintenance activities [29]. Goyal et al. [30] present an analytical model to reliably predict the health status of transformers, poles, and voltage regulators. Raghavan et al. [31] focus on the medium voltage domain and present a condition monitoring for 500kVA distribution network transformers with embedded fiber-optic sensors, which supervises vibration, temperature and corrosion. However, all of these research advances lack a proper holistic system design inherent in Information Systems research and rarely include the current status of the distribution grid. Further, they do not regard the current problems and expectations of electric utilities, thus, neglecting current problems of practitioners.

3 Research Method

Our overall goal is to design a system for data analysis and result presentation for condition-based maintenance on the distribution grid. Engineering these complex systems requires the development of innovative IT artifacts that fit the aforementioned requirements of condition-based maintenance and specific user requirements. To inform the design of these IT artifacts, we align to design science research as a research paradigm, supported by a qualitative study to infer valid design principles.

Design, on its own, is an artificial science [32], which refers to creating artifacts and resolving relevant problems. Design does not focus on describing how things are, but on how they ought to be to work properly [32]. In the IS domain, these theories for design and action are classified as valid research contributions in the field of design science research [33]. Design science research revolves around the design and evaluation of IT artifacts, which can be constructs, models, methods, or instantiations [34]. The contribution of design science research is twofold [35]: First, new theories for design and action contribute to the domain's knowledge base. Second, design science research outputs IT artifacts to solve real-world problems in applicable scenarios. The designed IT artifacts have to be evaluated in appropriate contexts to fulfill both contribution types [36].

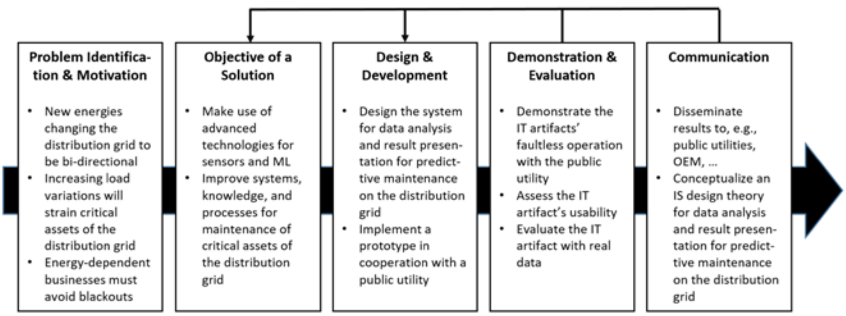

Figure 1. Complete Design Science Research Process (adapted from [37])

We approach our overall goal by following the design science research methodology of Peffers et al. [37]. Our instantiation of the research process is visualized in Figure 1. This study serves as a first part of achieving our research goal because we concentrate on design principles (DPs) without implementing and evaluating them, which we will do at a later stage (cf. Section 4.2, Section 5). DPs are results of design science research and represent justified statements or rules guiding and constraining design actions [37–39]. They are defined as "prescriptive statements that show how to do something to achieve a goal" [40]. We present our DPs by the conceptual schema for DP presentation by Gregor et al. [40]: DPs are characterized by their implementer, aim, user, context, mechanisms, enactors, and rationale. However, some components are not made explicit for some DPs [40]. As, in our paper, some components are identical for all DPs, we slightly change the way to present DPs, but include all components.

DPs will satisfy the model for design research in IS if they are rigor and relevant [34]. Therefore, we infer the DPs from kernel theories and business needs as contextual requirements. Our kernel theories are the theoretical background on maintenance strategies, especially condition-based maintenance. We also rely on other use cases of condition-based maintenance described in theories. For relevance, we have to assess the business needs and contextual requirements derived from the relevant contexts. In our case, this includes the owners of different parts of the distribution grid, who are responsible for the maintenance of critical assets. Thus, we interviewed six electric utilities in a qualitative study to gather insights on how condition-based maintenance systems must be designed to prevent issues and errors. The number of interviews saturated our results, such as more interviews would not result in more insights for the DPs. Thus, we can draw qualitative DPs from possibly subjective interview data.

Table 1 shows the electric utilities we interviewed. The grids maintained by the electric utilities vary in size concerning the number of stations, the area the distribution grid covers, and the employees of the utilities including employees managing the distribution grid, sales, marketing, and other internal services. For each interview partner we were able to simultaneously interview two employees with different backgrounds, mostly grid planning and maintenance. Many of these participants have a long experience in their profession and industry. Although we focus on medium voltage, the utilities' voltages range from low voltage to high voltage.

Table 1. Interview partners for our qualitative study

Interviewee	Voltage	Stations	Employees
Electric Utility 1	LV-MV	251-500	501-750
Electric Utility 2	LV-MV	251-500	251-500
Electric Utility 3	MV-HV	>10,000	751-1,000
Electric Utility 4	MV	<250	<250
Electric Utility 5	LV-MV	251-500	<250
Electric Utility 6	MV-HV	>5,000	>1,000

Our interviews consist of five different parts to generate qualitative data. We start each interview with an overview of the utilities' processes for maintenance and repair. Then, we acquire IT systems and status data currently available. We close off the analysis of the electric utilities' current state with an analysis of the value creation network and its stakeholders [41, 42]. Following, we investigate frequent errors and technical problems of their grid assets. Finally, we interview our partners for current tasks, pains, and gains, which could be achieved when overcoming specific pains [43]. This last step of our interview process builds the foundation for deriving design principles for a holistic maintenance system for the MV distribution grid. We aggregate the insights of each interview to gather a comprehensive list of system properties valid for all interviewees. As we already let our interviewees rank their tasks, pains, and gains throughout our interview, we can identify common threats and opportunities to improve maintenance on the distribution grid. With a combination of analyzing the state-of-the-art, problems, and wishes, we opt to understand how a system for condition-based maintenance with data analysis and result presentation to support electric utilities ought to be designed.

4 Results

4.1 Current Situation

Currently, electric utilities face an ambiguous situation. Their processes and IT systems are mature and well-defined. However, they have little to no insight into the situation of the critical assets of their distribution grid as SCADA systems for critical assets are rare. High cost pressure in the energy sector combined with frequently changing legal frameworks, makes utilities face uncertainties for the future.

The highest priority of activities concerning the electrical distribution grid is to secure permanent energy supply. Thus, fixing errors and reestablishing a fully functioning grid in case of a malfunction is critical to delivering energy to customers permanently. Our interview partners rely on customers to manually inform them in cases of missing energy supply through their contact center. In case of such an error notification, utilities try to react as quickly as possible. They are, however, in many cases, not able to identify occurring failures themselves, because they are missing condition data of their central assets. Although some partners have ideas to track and access condition data in the future, realization—and therefore, availability of data—is rare.

Errors and failures are often age-related and include cables, overhead transmission lines, transformers, circuit breakers, and switchgear. Many failures also occur due to accidents, e.g., groundwork and fallen trees. However, some failures leading to a breakdown of a station come from contamination or animals (mice, snakes) residing inside a station. This overview of failure cases aligns with statistics of failure cases of central components of the distribution grid [44, 45]. Critical errors increase with the age of central components.

Maintenance activities, including planned maintenance and inspection, are of less importance than incident management and installation activities. However, practice among utilities covers a wide spectrum of maintenance strategies. Some interviewees inspect their stations once per year and stick to strict maintenance intervals of four years. Others try to extend these intervals for cost concerns to more than eight years. Most senior distribution grid engineers have a precise knowledge of their stations and grid in general. However, most do not document this knowledge into existing systems. Also, maintenance and inspection intervals are not adapted based on the knowledge of stations, e.g., stations with a dirty environment (soot, dust) requiring more frequent maintenance. This, too, prevents reliability-centered maintenance strategies. Instead, the maintenance intervals are often based on forecasts of the component manufacturers.

Our interview partners apply established processes for the planning and installation of new components, maintenance, inspections, incident management, and replacement. In most cases, these processes are not digitalized and, as a result, not modeled into IS. Instead, the electric utilities mainly use four different classes of tools with different functionality. The first is geographic information systems (GISs), a unique form of IS with the purpose of measuring and representing geographic phenomena for collecting, storing, analyzing, and disseminating information about areas of the earth such as energy grids and its components [46, 47]. Energy providers use GISs for visualization purposes and to manage location-based information. Second, enterprise resource planning systems (ERP) provide the foundation for asset management and administration processes. Third, our interview partners make use of different IS for data management purposes. They create, save, and access different schemes, metadata, and manufacturer information about their components incorporated in the distribution grid. Fourth, there are many different tools for strategic management to plan and extend the grid. As some partners also use other systems, e.g., basic SCADA systems, the ones mentioned above are commonly used by all interview partners. The problem with the use of these systems is the missing integration. In many cases, data from one system cannot be accessed in another system, or the interface is unidirectional. This fosters redundancies and exacerbates the data management for central components of the distribution grid.

Concerning the value creation network, our interview partners maintain connections to various partners. The most important ones are the suppliers of energy, which can be power plants or high-voltage distribution grid operators, and the customers, which include private households, industry, and smaller distribution grid operators. The electric utilities often obtain components directly from component manufacturers. Further, there is some cooperation between different utilities, e.g., for using common tools and vehicles, providing help in cases of major incidents, and purchasing communities for improved price negotiations. Some interview partners also cooperate with software companies for customization purposes.

Summarizing, while the processes and systems handle daily business to keep incidents infrequently, cost pressure and staff shortage concerning quality and quantity arise. The conditions of legacy equipment are mostly unknown, and systems are not integrated properly, which bears an increased risk for the future stability of the distribution grid.

4.2 Design Principles

Following the six qualitative interviews, we derive eight DPs for a condition-based maintenance system on the distribution grid. We categorize them into three different groups to indicate their priority. First, high-priority DPs were mentioned by every interview partner and often categorized as important aspects (DP 1 and DP 2). Medium-priority DPs were either named by every interview partner, but with a low priority (DP 3), or only by some interviewees (DP 4 and DP 5). The DPs with a low priority were mentioned by one or two interview partners, while the other partners do not require a future condition-based maintenance system to comprise these mechanisms. Table 2 to 6 show the components of the five DPs prioritized high or medium. The context of each DP represents the surrounding elements and deficiencies of the current status. Following, we elaborate on the overall characteristics and specific aspects of the DPs.

We omit implementer and user as central components of a DP [40] because they are identical for all DPs derived from the interview data. We consider our project team comprising industry partners and research organizations as the implementer of the DPs in a system for data analysis and result presentation for condition-based maintenance. We want to continue our research process with the development of a prototype, as described in Figure 1. The prototype will then demonstrate the instantiations of our DPs, and we will evaluate our DPs based on different tests of the artifact. As we cooperate with one electric utility in our research project, we aim to evaluate the artifact in a testing scenario to prove the practical usability and relevance of the developed DPs. Therefore, all our DPs have an identical user characteristic of operators of the distribution grid, e.g., municipal utilities. Enactors specify the different user roles applying the mechanisms of the DPs through our IT artifact.

The rationale can include theoretical and empirical evidence to justify the proposition of a DP [40]. In our case, all proposed DPs were identified by the analysis of our qualitative interviews. As the electric utilities requested to be anonymized, we do not include direct citations into the description of the DPs. Instead, we enrich the DPs with literature supporting the aim and mechanism of our proposed DPs.

DP 1 focuses on the condition-based maintenance aspect of the artifact to be developed. It revolves around the algorithms necessary to predict upcoming failures and maintenance activities. The DP also contains the result presentation, which is twofold. First, the algorithms must output failure probabilities, which enactors can access through a dashboard for the status overview. A visualization should preferably be done in GISs, as GIS are already used in different scenarios by our interviewed partners. Second, the system should also output individual guidance for equipment soon to fail. However, DP 1 can only be deployed into an IT artifact if the foundations of DP 3—condition monitoring—are also implemented. DP 3 contains the basics of sensors and data necessary for algorithms to predict upcoming failures and therefore creates the technical basis for DP1. Though DP 1 and DP 3 are strongly related, as condition monitoring forms the foundation for condition-based maintenance [22], we deliberately list these two aspects separately, as condition monitoring is not necessarily only used for condition-based maintenance. For the condition monitoring, our interview partners need different data from their equipment, e.g., temperatures, loads, and data about air contamination inside the substations. For the results, the users want to access the current and historical data for further analysis and result interpretation purposes.

The second DP with a high priority is the only non-functional DP: system integration. During the interviews conducted, we noticed many complaints about redundant data, missing integration to have all data available in used systems, and too many manual activities to handle data. It is important to integrate the systems and avoid missing interfaces and redundancies because the interviewed partners do not have detailed status data already available. Thus, an increase in data will only worsen the existing problems if the systems are not well integrated. Furthermore, DP 2 contains the system types necessary for a holistic system: GIS, ERP (with asset management functionalities), and monitoring system (improvement of SCADA system). The algorithms described in DP 1 should be either integrated into one of these systems or into a separate system. Nevertheless, it is essential to integrate all systems bi-directionally, as system integration increases performance and the perceived success of a system [48]. We frame this as the kernel theory for DP 2.

DP 4 features documentation of incidents and maintenance. Previously, documentation was given the lowest priority by the interviewed partners. They did often not document and record their maintenance activities and were not able to report failure data. Although some interviewees used checklists for maintenance activities, the completed checklists were not stored. This DP aims to achieve an improved knowledge base by combining automatic documentation enriched with manual descriptions and standardized checklists. Errors and failures detected multiple times can easily be identified. This DP also includes a joint knowledge base for all maintenance-related activities. This is necessary because, previously, knowledge about specific equipment or stations was not stored in information systems. This DP is based on knowledge management systems supporting and enhancing the act of knowledge creation, storage, retrieval, and application [49]. There are different frameworks in Information Systems research and practice, e.g., ITIL for incident management [50], that can extend our condition-based maintenance system to a holistic system design.

Table 2. DP 1: Prediction of upcoming maintenance activities

Aim	Allow for increased planning certainty; allow for extended maintenance intervals; achieve a secure and continuous energy supply
Context	High cost pressure in the whole industry (missing budget for spare parts or replacements); rigid maintenance intervals; cause detection takes too long
Enablers	Algorithms; senior distribution grid engineer; control center
Mechanisms	Automatic detection of upcoming errors and information about equipment based on condition monitoring (DP 3); well-defined data; sophisticated algorithms (AI/ML) can interpret data; output of algorithms: failure probabilities, following: transparent and individual guidance; dashboard for status overview (failure probabilities) visualized with GIS
Rationale	Predictive maintenance [3, 22]

Table 3. DP 2: System integration

Aim	Achieve a higher system integration; achieve reduced redundancies
Context	Currently, there are too few interfaces; systems are not (well) integrated; data management is too much distributed
Enablers	Senior distribution grid engineer; field operations engineer; grid planning engineer; control center
Mechanisms	Avoid solitary systems; integrate GIS, ERP (including asset management), monitoring system; cross-system processes; interface for internal communication (dataflow, information flow, discussions); the systems has to be independent of component or equipment manufacturers
Rationale	System integration increases performance and perceived system success [48]

Table 4. DP 3: Condition monitoring

Aim	Allow for increased planning certainty; allow for reduced reaction times in error scenarios; achieve a secure and continuous energy supply
Context	Currently, most electric utilities have little or no data available; technicians cannot access information at electrical substations
Enablers	Sensors; senior distribution grid engineer; grid planning engineer; control center
Mechanisms	Sensors have to collect multiple types of data (e.g., air quality of substation to obtain "dirt-factor"); sensors have to be precise, robust, and reliable, such that they should need a minimum of maintenance themselves and have a low measuring tolerance; guidance on how many and which sensors to implement in a distribution grid depending on its size; users can access raw and historical data online; foundation for condition-based maintenance (DP 1)
Rationale	Condition monitoring and condition-based maintenance [22]

Table 5. DP 4: Incident and knowledge documentation

Aim	Achieve improved knowledge management; learn from errors
Context	Errors are not recorded and accounted; knowledge is often only to be found among senior distribution grid engineers and can be lost (e.g., by retirement and job changes)
Enablers	Senior distribution grid engineer; field operations engineer; grid planning engineer; control center
Mechanisms	Combine automatic and manual documentation of unexpected events (experiences, data peaks); error cause statistics; central knowledge base for special activities related to the distribution grid
Rationale	Knowledge management systems support and enhance the act of knowledge creation, storage, retrieval, and application [49]; frameworks for incident management such as ITIL [50]

Table 6. DP 5: Workforce management for maintenance

Aim	Allow for effective planning of staff for maintenance operations

Context	Quantity and quality of human resources on the market is critical
Enablers	Algorithms; senior distribution grid engineer
Mechanisms	Workforce management of internal resources for planning purposes; coordination of external service providers to counter staff shortage
Rationale	Workforce management systems increase service provider productivity [51]

The fifth DP describes mechanisms mentioned by only two of our interviewed partners. Interviewees wanted to have a workforce management system that allows for easy distribution of staff for maintenance activities. As not every grid operator can provide the necessary maintenance for their distribution grid, they cooperate with external service providers for maintenance. Thus, DP 5 targets both internal and external human resources for managing the workforce.

The DPs classified to have a low priority were only named by the minority of our interview partners. Thus, we consider the three low-priority DPs as optional. First, interview partners wanted to have an improved investment interval decision support based on condition data and asset type. This can be enabled by combining the data from DP 1 and DP 4 based on the foundations of decision support systems [52]. Second, some partners wanted to achieve higher system automation due to immature and incomplete SCADA systems. Mechanisms of performing automatic switch operations and accessing and viewing components via a remote control can achieve these aims. Third, some partners aimed for improved workplace safety by showing safety instructions according to the error and status data of other assets in the electric station.

5 Discussion

In recent years, condition-based maintenance has gained popularity in many sectors. Extending maintenance intervals and making them more flexible leads, among other things, to improved safety, reliability and availability, lower costs for parts and labor, and less waste in terms of raw materials and consumables [53]. Thus, switching from reactive or preventive to condition-based maintenance strategies holds promise. In our qualitative study, none of our informants' utilities apply predictive methods.

Contrary, condition-based maintenance is already being applied successfully by certain parts of the energy domain, e.g. power plants apply condition-based maintenance to prevent safety and cost issues [21]. We can observe a resemblance to the evolution of maintenance strategies and automation of the energy chain [2]. Starting from the power plants for energy generation towards transmission lines and transformers, both automation and maintenance strategy evolution decrease. After all, this is reasonable, because failures and shutdowns at energy generation result in a loss of power for a significantly higher number of households and industries, than failures or shutdowns at a local electric utility.

However, after more than 20 years of power plants applying condition-based maintenance, the question remains why electrical utilities refrain from applying advanced maintenance strategies. Reviewing related literature, we identified several reasons. First, system integration seems to be still a relevant problem. The peak of literature on system integration is already aged and proclaimed the rise of ERP systems [48, 54]. Our study shows that a use of ERP systems does not hinder the presence of difficulties from missing system integration. Potentially, switching to condition-based maintenance both as a maintenance strategy and as an information system can help to overcome existing problems, whereas implementing a standalone condition-based maintenance system bears the risk of aggravating existing problems. Second, electric utilities mostly utilize a variety of different assets [30] due to long lifespans, multiple manufacturers, and different environmental circumstances of their electrical stations. Some approaches successfully apply condition-based maintenance to central components of the distribution grid [29, 55], however, not for a majority of necessary components combined. Third, there is an immense lack of standards for condition-based maintenance systems and communication on the distribution grid. Fourth, the scalability of predictive solutions cannot be assured in many of its established applications. Having a mixture of geographic distributions in a range smaller than HV transmission lines is easier to maintain because of accessibility, but still makes it harder to manage than, e.g., power plants. Fifth, due to the different natures of assets it remains hard to track spatio-temporal deterioration.

6 Conclusion

With our qualitative interview study, we identified DPs for a data analysis and result presentation system using condition-based maintenance on the distribution grid. We contribute to the literature by displaying the current situation of electric utilities of different sizes and their risks and chances as their problems partially differ in comparison to problems mentioned in related literature. Our results show why a holistic assessment of the grid is challenging and how a system has to be designed to overcome these challenges. We also show room for improvement and aim to help electric utilities provide a system for secure energy provision in the future.

The selection of our interview partners limits our insights. We only focus on one country and interviewed six electrical utilities, but the results were saturated, and the last interviews only supported insights gained from the first ones. Also, we did not adequately evaluate the DPs, as necessary for proper design science research. However, this paper revolves around the qualitative insights from the interviews, neglecting an upcoming evaluation.

For further research, we aim to complete the design science process previously presented by discussing the design principles with electric utilities to propose advanced principles and by conceptualizing a complete system to support electric utilities. With a prototype, we can ensure a valid evaluation of this IT artifact and derive design knowledge for IS. An in-depth case study on why condition-based maintenance is not yet applied to the MV distribution grid could further enhance our insights.

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