Research Project SiNED Insights – Ancillary Services for Reliable Power Grids in Times of the Progressive German Energiewende and Digital Transformation

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Abstract

Ancillary services in future power systems have to be provided by decentralized distributed energy resources, resulting in various, interdisciplinary issues. Focusing on the three competence areas (Electrical Power Engineering, Digital Transformation/Information and Communication Technology, and Energy Law and Economics), insights for the central research goals of the project are presented (after three of five years of project duration). While results indicate, that the future ancillary services demand of a climate-neutral power system can be supplied with further developments, open questions and issues still remain. The interdisciplinary studies of the SiNED consortium show that it will be possible to provide ancillary services also from the lower voltage levels, both technically and economically. These results and the necessary regulatory frameworks are discussed in this paper.

1 Introduction and Motivation

The requirements and systemic integration of ancillary services (AS) will change significantly over the following years due to the transformation in the energy sector. Reasons are in the phase-out of larger power plants as well as an increase in electrification and sector coupling [1].

The central common research questions are considered to be: How can the changing demand for ASs, which increasingly have to be provided by decentralized distributed energy resources (DERs), be met in the future until 2045? How can the demand for ASs be met by the flexibility of prosumers, and how can this challenge be solved by converter-dominated distribution grids? How can flexibility for providing ASs in distribution grids be developed in terms of information technology, taking resilience into account? Which economic optimization potentials are possible for the provision of ASs, which (data protection) legal restrictions have to be considered, and which adjustments of the regulatory frameworks are necessary?

The interdisciplinary research project SiNED provides the results in different fields of expertise. The findings are presented according to the competence areas of SiNED, with section 2 focusing on electrical power engineering, section 3 on Digital Transformation/Information and Communication Technology (ICT), and section 4 on Energy Law and Economics. The results are concluded in section 5 and put in a broader perspective:

2 Electrical Power Engineering

2.1 Contributions to overall system stabilization in the transmission grid through coordinated ancillary service provision at the distribution grid level

In steady-state analyses, a Monte-Carlo simulation of uncertainties revealed that increased renewable penetrations cause increased and volatile power flows in the grid. As a result, technical bus voltage and line thermal constraints are at risk of violation [1]. This phenomenon

coupled with the future phase-out of thermal power plants poses challenges for the power system. Provision of ASs by flexible regulation of active and reactive power (PQ-flexibilities) in these power plants requires to be replaced by the increasing share of distributed energy resources. Since the DERs are primarily installed at the distribution grid level, a planned coordination of the ASs between the transmission and distribution grid level is required. A flexibility aggregation method is required to estimate the underlying distribution grid's PQ-flexibility potential. The aggregated flexibility subject to technical and grid constraints is termed a Feasible Operating Region [2]. A linear programming-based method is developed to aggregate PQ-flexibilities from medium-voltage (MV) and low-voltage (LV) grid levels [3] at the high voltage (HV)/MV interconnection. The fine-tuned flexibility aggregation method is validated against other methods, e.g., particle swarm-based optimization and quadratic programming. The advantages of fast-computation time for negligible loss of quality are highlighted. Current extensions for aggregating flexibilities from the HV grid across multiple extra high voltage (EHV)/HV grid interconnections are being developed. The situation in meshed HV grid with multiple HV/EHV interconnections is more complex as the proximity of flexibilities to the interconnections requires consideration. Power transfer distribution factors across the interconnections can be used to identify and influence interconnection power flows according to proximal flexibilities. Integration in a multi-objective optimization environment to prioritize flexibilities across different interconnections results in a combinatorial problem. Furthermore, effective applications of the aggregated MV grid PQ-flexibilities to address voltage limit violations and congestions at the HV grid level are being studied.
In dynamic analyses, frequency containment reserve (FCR) methods are developed on an established benchmark test grid. Approaches like hidden inertia emulation and pitch control-based techniques are studied. The developments are further being extended for application in large-scale dynamic power grids. Therefore, a dynamic transmission power grid of Germany is modelled with aggregated bus power injections/demands from the underlying voltage levels. The FCR techniques extend correspondingly, considering aggregated flexibilities with wind and solar power plants.

2.2 Demand analysis, control engineering, and concepts for ancillary services for the compensation of fast load jumps in distribution networks

ASs are part of the stabilization of power grids. To ensure reliable operation of future grids, a demand analysis for the DERs in the individual voltage levels of the distribution grid was conducted [1].
For LV levels, a validation environment was set up and designed, allowing validation of the developed control algorithm for the provision of local ASs. With machine-learning-based reactive power management, a grid laboratory environment test has already been successfully completed [4].
A control algorithm for providing global ASs of automatic frequency restoration reserve (aFRR) from the MV level was developed to investigate the use of DERs for frequency control. The algorithm was validated by simulation in an isolated micro-grid to analyze the possibility and system boundaries. The two-staged controller was developed in MATLAB/Simulink and calculated a target value of the power demanded for frequency stabilization. In the second step, the power is distributed to a selected group of power units. If the model is transferred to reality, these units are prequalified providers for aFRR. The simulation showed that the system limits are defined by the total maximum power provided by the power units and the predefined response time [5].
Due to the lack of inertia in an isolated micro-grid, the response times of the aFRR-control must be adjusted.Within the system limits, the algorithm achieves frequency stability in the grid. Subsequently the algorithm will be implemented and validated in a grid laboratory environment using the methodological approach of a grid-in-the-loop environment (GIL). The procedure from the model to the laboratory is presented in **Figure 1**. With this GIL approach, it is possible to validate algorithms that have a higher-level impact on grid operation in a laboratory environment and to investigate the interaction and impact between multiple stakeholders in the grid.
A three-phase rapid control prototyping inverter platform is used to test the prototypical algorithms and investigate the dynamic influences and effects on the grid and its operation. A plant-equivalent simulation model was designed in MATLAB/Simulink. Accordingly, it is possible to validate developed algorithms prototypically, in simulation and hardware-based environments.

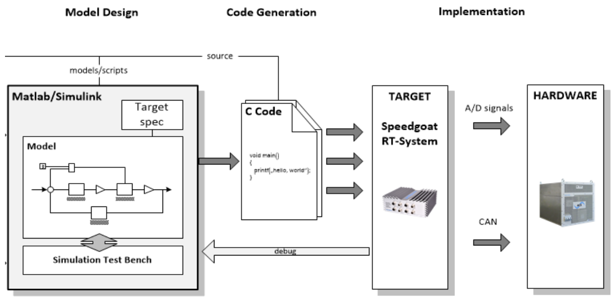

Figure 1 Structure of simulative and hardware-based development of control algorithms

2.3 Ancillary services of the grid-serving prosumer with storage, photovoltaics, electromobility and heat pump

In investigations of a grid-serving prosumer with a photovoltaic system, battery storage system (BSS), electric vehicle (EV) and heat pump, the impact of the evolution of households on the power grids is assessed. It is to be mentioned that these comparatively large prosumer devices have a significant impact on critical grid situations (reliability) in the LV grid [1]. Based on the higher estimated active and reactive power values at the grid connection points, the utilization of grid components will consequently increase. On the other hand, the power engineering prosumer devices offer a high degree of flexibility [1], for example, in shifting EV or BSS charging processes. This flexibility can be used to integrate the provision of AS without negatively impacting the primary use (e.g., maximization of self-consumption) [6]. Based on a qualitative estimation, prosumer devices with their inverter technologies seem well suited to offer local AS like voltage control or congestion management. When aggregated with other devices, they may even be suitable to provide reserve power for frequency control as a global AS.

Several simulative studies are made with the simulation environment eSE [7] to estimate the influence of grid-serving behavior from prosumers. At first, a centralized coordination approach is developed as an AS model, which determines the demand of AS in the LV grid based on a power-flow calculation and tries to efficiently cover the demand with flexibility from prosumer devices using sensitivity factors to quantify the impact. [8] Early results show the potential to completely eliminate violations for the LV grid as the current grid status and the impact of a power adaption is considered. Other concepts are decentral approaches where the grid operator can only impose certain boundary ranges (e. g. a specific range of active power provision at the grid connection point) or prescribe specific reactional behavior in the form of characteristic curves (e. g. for voltage control concepts in inverter-based devices). Different voltage control concepts for the generation, consumption, and storage devices in prosumer households have been investigated [9] with the conclusion that the concepts have a positive impact on voltage control, but to a different extent and with different effects on other relevant key figures like economic efficiency. It was found, that the optimal the grid operator's prescribed voltage control concepts, as well as the fact that a shift of (dis)charging processes is more critical than a voltage control concept with residential BSS.

Future work regarding grid-serving prosumers will include a detailed look at the provision of frequency control as a global AS. Additionally, the technical synergies of the multi-use of BSS in the form of grid-serving operating strategies are to be examined. Furthermore, a comparison of innovative grid components like controllable local power transformers is planned.

2.4 Protection systems in networks with distributed converters

ASs will be provided more and more by inverter-based systems in the distribution grid. A reassessment of conventional protection systems is essential, as there is increasing variation in power-flow directions, a decrease in short-circuit levels, and a change of the overall grid topologies and dynamics caused by the inverter control and protection concepts. These aspects negatively influence conventional protection systems' functionality, which is blinding, sympathetic tripping, and loss of coordination, as stated in [10].

In order to evaluate these findings and for the development and validation of modern protection concepts, a simulation model has been implemented in MATLAB/Simulink, which consists of an excerpt of a Cigré MV benchmark system, distance and overcurrent protection systems, and inverter-based infeed with dynamics compliant with VDE-AR-N 4110:2018. The model has been described in more detail in [1].

Simulation results of various fault scenarios have been analyzed in detail with the core statement that especially the feeder distance protection system functionality could be negatively influenced when inverter-based systems are in intermediate infeed configurations, leading to overreach/underreach, errors in fault location estimation and loss of backup protection. This is also supported by literature [11]. **Figure 2** shows such a configuration.

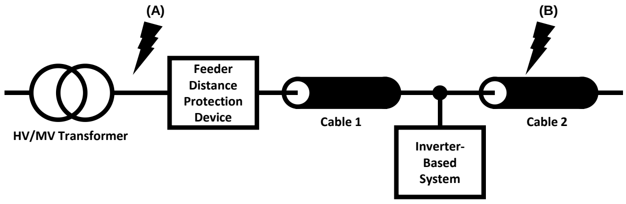

Figure 2 Fault locations (A) and (B) that negatively influence the feeder distance protection device due to intermediate infeed that results in error impedances

Fault (A) leads to a short-circuit current contribution of the inverter-based system, which is reversed to the conventional direction without such infeed. Other protection measures would still lead to a fast disconnection of the faulty branch, but a false tripping without these measures would be possible. Fault (B) leads to error impedances that negatively influence fault location and create overreach/underreach issues for this device.

There are various concepts and algorithms to overcome these challenges, with a review following in another publication. In general, they can be classified into the adaption of the protection systems themselves and the adaption of the inverter controls. Here, the distance protection system functionality has been enhanced by a direction recognition algorithm long considered state-of-the-art. Then, the negative impact of fault (A) on the protection system can be reduced completely, which has been validated with the developed simulation model.

For improving the performance when fault (B) is present, two algorithms have been developed. One considers the adaption of inverter-based controls, which will be presented in [12]. The other one relies on measurements at the Point of Common Coupling of the inverter-based system. Currents and voltages are communicated to the feeder distance protection device, which enables the possibility to eliminate the error impedance. Then, the device's settings can remain as is. The principle has been validated with simulations. Further investigations have to be performed as the communication needs to be fast and over long distances. It will be analyzed whether this issue can be resolved by implementing additional algorithms that can predict the grid's state with sparse information, eliminating the need for a strong communication system. What follows is that the algorithms developed and evaluated in a simulation environment will also be validated with laboratory-scale experiments.

3 Digital Transformation / Information and Communication Technology

3.1 Information technology platforms and services for the provision of decentralized ancillary services

A service information technology (IT) platform for the provision of decentralized ASs was developed using standardized requirement analysis. Three use cases (UC) with different objectives were designed to evaluate the functionality and performance of the service platform and then documented along IEC PAS 62559.

- UC1: Calculating correlations between arbitrary time series with several different correlation functions;
- UC2: Prediction of joint reliabilities of a coalition to provide ASs;
- UC3: Reliability-sensitive optimization for the provision of ASs.

The architecture of the proposed service platform that is shown in **Figure 3**, contains four main modules: communication and management layer, database, service, and user interface. Connections between parts are implemented through REST APIs, and all modules are dockerized. Different algorithms were already developed and integrated into the service platform. These algorithms are designed such that the output of one of them is the input to the next stage, classified as follows: 1) data preparation, 2) uncertainty modeling, 3) decomposition of the multivariate correlation problem using pair-copula functions, 4) computing the proper copula family, 5) visualizing the correlation graph, 6) generating synthetic data, 7) fitting probability distribution function to the error histograms, 8) computing the joint-reliability model, 9) Selecting the desired AS, 10) reliability-sensitive optimization.

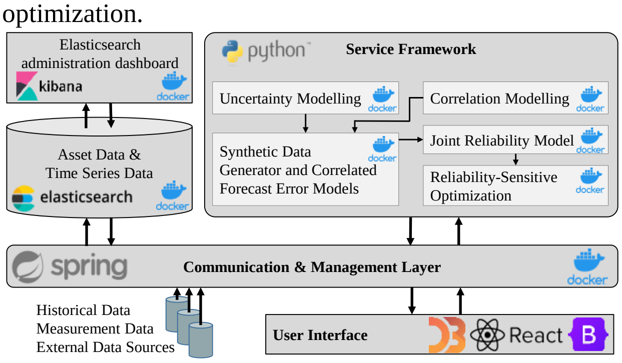

Figure 3 The proposed modular service (IT) platform

3.2 Data, transaction and service concepts for forecasting, deployment planning and marketing of automated and autonomous activation of decentralized ancillary services

In this work package, an agent-based energy market model was developed to simulate the procurement and activation of ASs from the transmission as well as the distribution grid. The model simulates hierarchical reserve power auctions, which are carried out by market operators (MO) and market participants (MP) (each implemented as agents) based on assumptions from [13]. MPs size their bids based on a flexibility model of the connected DER (e. g. BSS), which is simulated separately in a co-simulation approach. As the platform connects decentralized grid areas, special challenges arise concerning the synchronization of bids and market results in the interaction between the distribution system operator (DSO) and the transmission system operator (TSO). Considering placed bids, MOs perform a market clearing of which the result affects which DER has to provide flexibility. This changes their future state values, affecting future flexibility planning and bid sizing.

The TSO-DSO interaction was developed based on cooperation schemes from [14] and is displayed in **Figure 4**. To allow DSOs to operate their grids independently, bids from connected MPs are placed locally independent from the procuring SO. In [13], such a process is included in the local AS market scheme. There, it merely serves the purpose that DSOs can reject bids if they violate local constraints. In the presented project, the DSO can increase the locally procured amount of frequency control capacity for potential emergencies of island operation, while the procurement of the TSO is not delimitated.

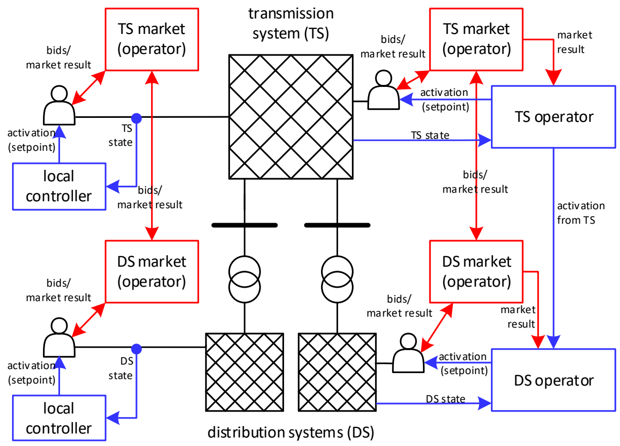

Figure 4 Coordination scheme of hierarchical control reserve market. A decentralized activation (e.g. like in case of FCR) is represented on the left and an activation by setpoints from the SO is shown on the right. (e.g. like in case of aFRR). Red represents market processes and blue represents those relevant for the activation.

The planning and bid sizing of the MPs considers locally operated devices. A flexible BSS model was developed and published in [15]. Planning considers the current state of a battery, a load forecast for peak shaving, and already placed or awarded bids. Plausibility checks showed an expected behavior of the model, and the next steps are to integrate key performance indicators for an economic evaluation of the simulation.

In parallel, the implementation of such a hierarchical auction on distributed ledger technology is examined. A linking of independent blockchains via smart contracts and the use of BlockDAG/Sharding are under development. It is based on the partitioning algorithm presented in [16], which relies on the bitcoin blockchain. Further steps are to transfer this algorithm to a smart-contract capable blockchain implementation.

3.3 AI tools and frameworks for power flow forecasting and attack vectors on ICT infrastructures

Since electricity generation from renewable energy sources is subject to large weather-related fluctuations, accurate electricity generation forecasts are relevant to maintaining supply security [17]. Artificial intelligence (AI) applications can make a crucial contribution. For example, machine learning (ML) processes enable increased forecast accuracy in numerous application areas [17]. Since these processes are implemented through AI frameworks, their application is investigated. Thus, the AI frameworks Scikit-learn[1], Keras[2], and PyTorch[3] will be used to implement artificial neural network models, after which a performance comparison will be made. In addition, the frameworks are also compared in terms of their usability, documentation, quality of service, and training duration.

As a result, Scikit-learn combines ease of use, clear documentation, and short training duration with a prediction accuracy comparable to the performances of the other frameworks. Furthermore, Scikit-learn allows a fast implementation and comparison of different ML models. If a use case requires the use of more flexible artificial neural networks, Keras is a suitable tool. It allows all configuration options that might be relevant for regression tasks. Although PyTorch offers the widest range of configuration options, most of these are not needed for time series forecasting of power generation data. Since using PyTorch involves increased complexity and coding effort, the other frameworks are better alternatives for the considered use case.

To identify cyber protection strategies and deduce possible attack vectors on ICT infrastructures, in taxonomy 229, AI-driven cybersecurity services were classified regarding their protection target, provided service, response strategy, and concept of security information [18]. Based on the results, four cyber protection strategies were identified. The first strategy involves intrusion detection and resilience-enhancing cybersecurity options through ML-based scanning of internal business systems and the internet. The key objective is to identify vulnerabilities and threats. The second strategy involves ML technology utilization to detect and respond to anomalies and attacks in real-time. This facilitates resilience, prevention, intrusion detection, and response to cyberattacks. The third strategy enhances the achievement of governance and compliance regulations. Data management, risk analysis, penetration testing, logins, and two-factor authentication are typical functions. The fourth strategy includes attack prevention solutions with an automated response approach by scanning business internal systems, dark and deep web, internet, and social media. Based on these results, the most common attack vectors are phishing attacks, ransomware and data leaks, bot attacks, and disinformation. In addition, social media, the dark and deep web represent potential attack channels for both third-party and first-party attackers. In [18], it has been shown that AI technology can improve essential functions such as threat monitoring and mitigation, risk mapping, and threat emulation.

4 Energy Law and Economics

4.1 Fair pricing of ancillary services and economic potentials of controllable renewable energies

To investigate the pricing of ASs and to make a statement about their fairness, i.e., market-oriented pricing, 13 interviews with TSO, DSO and plant operators were conducted and qualitatively analyzed. The focus is on control power, especially aFRR. The financial goal of control power marketing is to be above the mean value of the bids, i.e., above the benchmark, in the long term. The bidding strategies depend on the plant portfolio of the plant operator or the marketer and their risk aversion. In general, five different bid strategies can be distinguished: (1) standard bids, (2) lucky bids, (3) opportunistic bids, (4) aggressive bids, and (5) exit strategy. In standard bidding, the service is offered at the expected service and energy prices that can be justified. Work prices are based on the marginal cost of the equipment (usually, energy prices are submitted equal). Lucky bids offer the last capacity in the portfolio at very high energy and power prices. These prices are usually not marketable. Opportunistic bids are bids for plants not permanently connected to the grid or in operation. The capacity of such plants, e.g., heating rods in negative control reserve, is offered at very high prices. In case of a surcharge and a call, the plants are started. Otherwise, the plant remains off. The strategy behind aggressive bidding is to offer capacity at high prices on the control reserve market. Failure to bid is not fatal because the opportunity of the energy market still exists. This strategy is more likely to be used by big players. The last is the exit strategy, where an extremely high energy price is offered. This strategy is used to push capacity out of the

[1] https://scikit-learn.org/stable/#
[2] https://keras.io/
[3] https://pytorch.org/

merit order because, for example, the designated plant is damaged or other markets are more lucrative.

To examine controllable DER for providing distributed ASs, decentralized energy solutions and energy trading in microgrids play a special role. For this purpose, technical-operational simulations and a linear optimization procedure were developed to analyze the impact of microgrid trading in different scenarios. Furthermore, a model extension was developed to investigate the possibilities of a microgrid to offer balancing energy. For the numerical analysis, different realistic environmental scenarios with different penetration levels of renewable energy use were developed. The scenarios also integrate the coupling of solar and wind power generation and the provision of balancing power. In addition to the linear optimization procedure, a web-based simulation tool for nano-energy systems called NESSI[4] was also developed, simulating buildings and neighborhoods in terms of energy demand and generation of many components. NESSI facilitates the quantification of the environmental, economic, and social impacts of an individual energy system and thus the identification of a suitable energy system for an individual location. This involves new buildings but also the transformation of existing buildings. Based on this, transformation strategies can also be formulated and thus support the local, German and global energy transition. The empirical results show that microgrid trading provides incentives for renewable energy generation by reducing participants' energy costs and increasing revenues from electricity generation. In particular, the savings from integrating wind energy and offering balancing power are significant. Controllable integration of biogas plants can also contribute significantly to electricity and heat supply. Overall, economic optimization potentials can only be identified if investments are made in acquiring storage technologies and wind or biogas plants.

4.2 Legal framework for ancillary services

Legal aspects considered in the project cover three main topics: The procurement of demand-side flexibility for congestion management, legal requirements regarding data use, and the multi-purpose use of battery storage.

The study regarding the regulatory framework for congestion management focused primarily on different approaches for the procurement of demand side flexibility. Whereas the first period of SiNED focused on mechanisms, which procure flexibility only at the occurrence of a bottleneck in the grid, in the second SiNED period the focus of study was laid on mechanisms which procure the flexibility in advance for a specified period of time, regardless of the existence of a congestion. This second kind of mechanism is characterized by a legal relationship between the grid operator and the flexibility provider, which enables the former to access the flexibility of the plant. Because the procurement mechanism applies to a longer period, the legal relationship is more complex and can be shaped in different ways. The detailed arrangements must particularly regulate the duration of the contractual obligation, the remuneration model and the general conditions of the right of use. For a market-based approach, criteria were established that must be fulfilled by the remuneration to be paid out. Furthermore, three possible methods for determining compensation were identified and compared. In addition, the general advantages and disadvantages of a stand-alone remuneration and an incentive via a network charge reduction were compared.

A deviation from market-based procurement is possible if economic inefficiencies are to be expected due to the effect of market failure (Art. 13 (3) of Regulation No. 943/2019; Art. 32 (1) of Directive No. 2019/944). Non-market-based mechanisms are characterized by the mandatory participation of the flexibility provider. It was found that also non-market-based approaches generally require some form of remuneration for the participation of the flexibility provider. However, exceptions can be made in specific cases where the grid operator has fulfilled all legal requirements with regards to the necessary expansion of his grid. A mandatory participation in such an instrument represents an encroachment on various fundamental rights of the flexibility provider. Nevertheless, the instrument can generally be considered proportionate, especially if extraordinary (individual) situations are considered where the measures cause an unusual burden, for instance, in the form of exceptions.

Another focus of the study was the legal framework for the use of grid-related data by different actors. It was determined that especially new market roles, such as aggregators, and data processing in blockchain applications, face restrictions. Within the scope of the German Messstellenbetriebsgesetz (MsbG), the processing of data must either be based on consent of the data subject, fulfillment of a contract, be required in preparation for a contract the affected party initiated or be necessary to fulfill a legal obligation stemming from the MsbG or certain other laws or to fulfill a task in the exercise of official authority vested in a grid operator. These restrictions aim to protect personal data, ensure cybersecurity, and protect competition. [19] With a similar purpose, the actors that may handle personal data are listed conclusively. While aggregators are not included in this list, they may process data based on consent**.** This option ensures compliance with the demands of the General Data Protection Regulation (GDPR), but may pose difficulties as the consent can be withdrawn at any point. Similarly, the fact that data in a blockchain is processed by every participant may stand in contrast to this requirement of a specific purpose of data processing, as well as the limited number of actors permitted to process data and the principle of data minimization as set forth by the GDPR. However, the use of permissioned or private blockchain may offer a solution for these issues and is compatible with use cases for the electricity sector.

[4] nessi.iwi.uni-hannover.de

Finally, hurdles for a multi-purpose use of electricity storage facilities were discussed. While a serious financial strain was relieved when in July 2022 the EEG surcharge (EEG-Umlage) was dropped, another difficulty for the multi-purpose use of electricity storage remains in the form of network charges. These generally apply for the consumption of electricity. Since electricity storage currently is considered by the German legislator as a combination of electricity consumption and generation, electricity that has been stored could face these charges twice: for the consumption in the storage and for the final consumption elsewhere. Whilst exceptions exist, there remain situations where this double charge still applies e.g., when the storage has been in use for over twenty years. Double charges possibly also apply when the electricity stored is not fully fed back into the grid. Finally, the so-called "Ausschließlichkeitsprinzip" (principle of exclusivity) may hinder the storage of electricity from different sources within one storage unit. This is the case because the right to certain subsidies for the use of renewable energy can be jeopardized when a storage is not charged exclusively with energy from renewable sources. This may stand in contrast to European regulations requiring Member States to take certain measures to encourage the use of storage solutions.

5 Conclusion and Outlook

In conclusion, a variety of concepts, results, and implementations were achieved during the project.

In the area of electrical power engineering, aspects of different voltage levels and fault handling were investigated. Based on the impact of changes detected at the household level and the flexibility potential of prosumers, algorithms were developed to provide ASs with the distributed devices and a simulative and hardware-based validation environment was built. The aggregation of distribution grid flexibilities for usage in operation of overlaying grid levels is proposed and in dynamic analyses, FCR techniques from DERs are investigated. The evaluation of protection and control systems shows that further development of distance protection systems are necessary to ensure a safe and reliable provision of ASs with increasing inverter-based infeed. The prospective, distributed provision of flexibility services for grid operations in a digitalized way requires developing IT and corresponding ICT infrastructures.

Therefore, an IT service platform to aggregate DER flexibility and a decentralized market architecture for the resilient provision of ASs were developed and implemented for an agent-based simulation. Cyber security aspects of ICT infrastructures in the form of cyber-attack vectors and cyber security strategies were also considered. The bid-based design of the AS market influences the financial factors of the market in terms of the scope and diversity of the asset portfolio and the risk aversion of the marketer. With regard to legal aspects, it was established that whilst hurdles still exist in some areas, there are forms of procurement of flexibility, market designs, data use as well as battery storage applications that allow to meet the demands of a transitioning energy system. To conclude, these interim results indicate the technical economics and regulatory feasibility of the future provision of AS by DER. But they also show the need for further research on ASs, which require to be addressed in the second phase of the project SiNED.

6 Acknowledgement

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