Towards a Real-World Dispatchable Feeder

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***Abstract*—With the integration of renewable energy sources, electric vehicles, and batteries at the low-voltage distribution grid level, residential buildings are increasingly evolving from consumers to prosumers. As the prosumers burden the distribution grid with their uncertain interactions, the need for solutions to counteract this uncertainty becomes more important. One such solution is schedule-based control strategies, such as the dispatchable feeder. Thereby, the dispatchable feeder uses intelligent managed flexible components such as battery energy storage system (BESS) and controllable loads to follow a committed schedule. While the concept of the dispatchable feeder is widely discussed in the literature, the practical challenges associated with its real-world implementation remain underexplored. Therefore, this paper identifies challenges associated with the real-world implementation of the dispatchable feeder in residential buildings. Further, it discusses important future research questions regarding the concept and its valuable integration into the real world. It also proposes an experimental research infrastructure for systematically investigating the raised questions using the real-world laboratory of the Energy Lab 2.0.**

***Index Terms*—Energy management, active distribution networks, dispatchability, dispatchable feeder, scheduling, real-world requirements and implementations**

I. Introduction

The energy transition encourages a large-scale expansion of renewable energy sources, most of which are integrated into the distribution grid. For photovoltaic systems, this expansion is being driven by legislation, such as the PVPf-VO in Baden-Württemberg in Germany [1], which requires owners to install photovoltaic systems on all major roof renovations and new buildings, and the coalition agreement of the German government, which aims to use all suitable roof areas for solar energy in the future [2]. This obligation is complemented by the voluntary expansion of rooftop and balcony power plants, resulting in a large number of distributed energy resources (DERs) among energy consumers. As a result, consumers are increasingly becoming prosumers, producers and consumers all at once.

In addition to generation, the prosumer's consumption is also becoming both larger in terms of potential peak load and more dynamic in load profile as DERs are often coupled with heat pumps, battery energy storage systems (BESSs), and electric vehicles (EVs). All these components can be controlled individually, therefore, the individual prosumer decides its own actions to manage the building and interact with the distribution grid. Those prosumer actions generate uncertainties, especially in the low-voltage distribution grid and a need to foresee, control and regularize the actions of the prosumer.

Concepts to deal with the variety of actions on the prosumer side are schedule-based control strategies, such as the dispatchable feeder (DF) [3], [4]. More precisely, to counteract the uncertainty, the DF intelligently manages flexible components such as BESS and controllable loads to follow a day-ahead schedule. While some works on the DF include real-world aspects in their mathematical description [5]–[8], they only verify their approaches via simulation. Some works address the real-world implementation of DF concepts at the medium-voltage level [3], [9], [10] but specific aspects of the low-voltage distribution level are lacking.

Therefore, the main contributions of this paper are the following:

- The presentation of observed challenges and the identification of potential research questions arising from the real-world implementation of the DF concept at the low-voltage distribution level, such as hardware constraints, uncoordinated systems, and temporal resolution.
- The presentation of an experimental research infrastructure at the low-voltage distribution level for the systematic investigation of the described research questions.

The remainder of this paper is organized as follows: Section II presents the existing literature on the DFs and their real-world implementation. Section III describes the concept of the DF before presenting the challenges of the real-world implementation. Based on this, research questions are identified and the experimental research infrastructure is presented. Finally, Section IV concludes the paper.

II. Related Work

Since DFs are a subcategory of energy management and control strategies, we first present related work on the general objectives of energy management and control strategies. Second, we describe the previous work on the subcategory of schedule-based control strategies to which DFs belong with respect to their real-world implementation.

A. Energy management and control strategies

Energy management and control strategies cover a wide range of goals and algorithms and show increasing relevance in the research community. A comprehensive review of recent activities related to energy management and control strategies for microgrid applications is conducted in [11]. The authors categorize research regarding energy management and control strategies into structural aspects and operational aspects. In terms of structural aspects, a distinction is made between centralized, decentralized, and distributed control schemes. Operational aspects of energy management and control strategies are forecasting, optimization, and real-time control. The operation of the optimization is dictated by a variety of objectives like load shedding, minimization of operating expenses, avoiding greenhouse gas emissions or maximizing trading profits [11].

The goals of minimizing operating expenses and emissions or maximizing user comfort can also be found in other works regarding schedule-based strategies like [12]–[14]. The authors of [14] further differentiate the goals of energy management and control strategies into economic, technical, and others. More technical goals, such as voltage and frequency stability, as well as power quality assurance, are presented in [14]. Grid-serving goals of energy management and control strategies are mentioned by [13] in the form of grid support and the consideration of power limits. Research in the field of energy management and control strategies field has generally moved from theoretical and simulation modeling to practical implementations and actual use cases, with many projects completed worldwide [15].

B. Schedule-based control strategies and their real-world implementation

As there is a variety of different components influencing the reactive and active power, it is necessary to take a closer look at the different components. [16] suggests an algorithm combining scheduled-based control with real flexibility profiles of the individual components like P-Q-curves to be able to adapt to more realistic use cases. They also consider line losses in their calculation for the interaction between the components. [17] describes the implementation of this concept in a simulated environment acting as a feeder at the point of common coupling (PCC) to the medium voltage level.

One concept of a schedule-based control strategy is the DF. The DF can be modeled using an optimization problem that takes into account real-world characteristics [5]–[8].

In contrast to simulated scenarios, there are only a few real-world implementations. However, these implementations involve several office buildings, serving as a higher aggregated baseload and causing fewer dynamic gradients. Additionally, the PV system is smaller than the baseload of the buildings and can therefore be compensated by a large and powerful industrial BESS [3], [9], [10], [18]. Furthermore, the implementation concerns the aggregated feed-in at the medium-voltage level.

Moreover, [18] describes a Living Lab Energy Campus (LLEC) as a research area with several industrial, research and office buildings for also testing schedule-based control strategies. However, the majority of buildings are larger in consumption and therefore coupled through the medium voltage grid.

In summary, the existing real-world implementations have several drawbacks regarding the study of the impact of a DF implementation in an all-encompassing manner. On the one hand, most existing implementations focus on larger office or research buildings that are connected to the medium voltage level, and therefore do not consider the high dynamics of small residential buildings with high PV power generation in relation to their baseload. On the other hand, in some implementations, the authors only used PHIL for various components, which cannot fully represent real-world hardware characteristics.

III. From concept to real-world (an iterative process)

In order to transfer the concept of the DF into real-world implementation, we first present the concept of the DF in Subsection III-A. Afterwards, as some hardware and software aspects for the real-world implementation of the DF are not known in advance, we perform a proof of concept study in Subsection III-B. Based on these two sections, we elaborate potential research questions in Subsection III-C. To answer these research questions, we list requirements for the experimental research infrastructure in Subsection III-D. Finally, with this list of requirements, we develop and present the experimental research infrastructure in Subsection III-E.

A. Concept of the dispatchable feeder

The dispatchable feeder consists of an inflexible component and a flexible, but energy-constrained component, as illustrated in Figure 1. Typically, the inflexible component considers uncertain, volatile load and renewable energy sources from the same unit, referred to as prosumption and denoted as $P_l \in \mathbb{R}$.

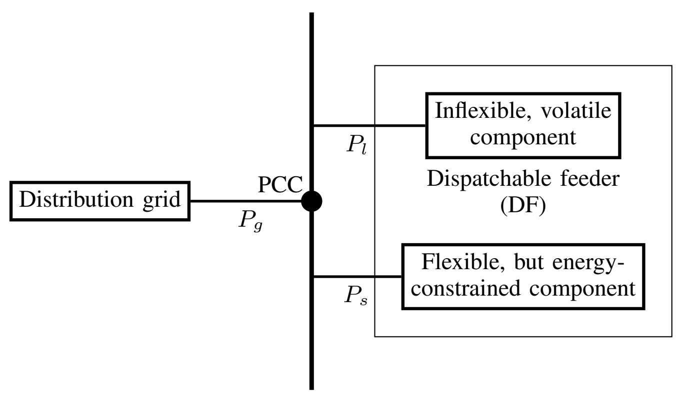

Fig. 1: The DF combines an inflexible, volatile component with a flexible, but energy-constrained component. Thereby, the prosumption is denoted with P_l and the power output of the flexible component as P_s. Furthermore, the power exchange between the grid and the DF is P_g (adapted from [4]).

The flexibility is typically provided by a BESS and controllable loads, represented by $P_s \in \mathbb{R}$. Both components are connected to the grid through a bus at the PCC, and the power exchange with the grid is denoted as $P_g \in \mathbb{R}$. The primary objective of the DF is to ensure the reliability of its committed schedule through intelligent management of the flexible component. This is achieved by solving a hierarchical scheduling problem. First, a day-ahead schedule of P_g is optimized with respect to an ancillary objective, such as energy cost minimization, taking prosumption forecasts into account. Second, an underlying control scheme minimizes deviations from the scheduled power exchange P_g by managing the flexible component.

Thus, the formulation and simplification of the scheduling problem during modeling are crucial for the successful real-world implementation of the DF. One such simplification arises from the temporal discretization of the continuous power quantities. For example, the power quantities are modeled over time intervals of a defined duration which we refer to as temporal resolution. The power quantity of a particular time interval then corresponds to its average value over that time interval. Another simplification comes with the BESS model, which describes how the power input to the BESS is translated into its State of Energy (SoE).

Such simplifications raise questions about the transfer of the conceptual model to the real world, which we aim to elaborate in the following.

B. Proof of Concept study

In order to identify the challenges of the real-world implementation of the DF concept and to lay the foundation for a large-scale infrastructure, we build a straightforward DF prototype. The prototype is based on the daily load of a small residential building with a $9\,\mathrm{kWp}$ PV system. The inflexible prosumption consists then of the building load minus the PV power generation. As a flexible component, we consider a BESS with a rated power of $3\,\mathrm{kW}$ and a capacity of $19.5\,\mathrm{kWh}$. With this BESS, we try to follow a schedule that we derived from a comparable previous day with a temporal resolution of $15\,\mathrm{min}$.

Figure 2 shows the committed schedule. Based on this schedule, the BESS control system regulates the power to follow the schedule. The BESS control system uses the difference between the scheduled value and the current power at the PCC to calculate a setpoint for the power electronics. To suppress swing effects between the BESS and the PV system caused by dead times in the BESS control system, a moving average filter is applied to all setpoints. For example, between 11:30 and 11:45, the measured power at the PCC follows the scheduled value closely during this time interval. For the time interval between 11:45 and 12:00, we see over a short period of time a high gradient with a deviation from the schedule of around $6\,\mathrm{kW}$ which is the result of a sudden drop of the PV power generation (compare Figure 3) possibly caused by a cloud. Even for this simple example, the challenges of following a schedule are apparent. It is important to realize that the $15\,\mathrm{min}$ temporal resolution of the dispatch schedule makes it very difficult to guarantee the same power at all times during this time interval and high gradients (for example clouds on the PV side or EV on the load side) are propagated directly to the grid. This leads to an oscillation around the scheduled value due to dead times and communication delays which have to be investigated.

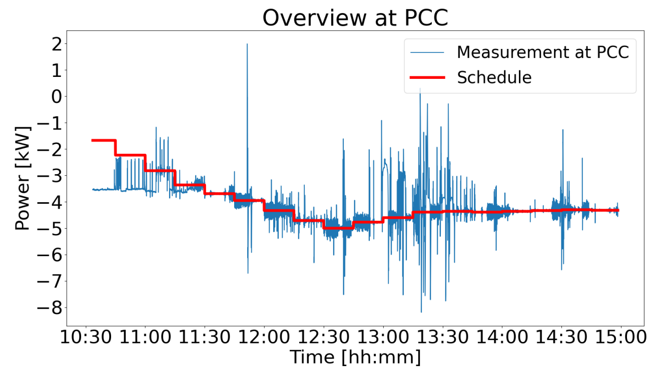

Fig. 2: Measurement data at the point of common coupling (blue line) and the committed schedule (red line)

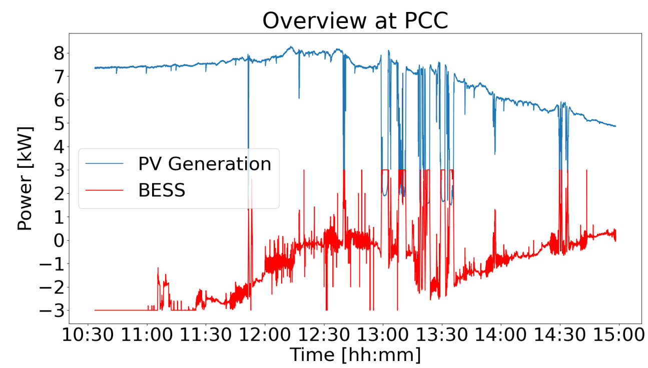

Fig. 3: Measurement data of the PV power generation (blue line) and power of BESS (red line)

C. Identification of research questions in hard- and software

The proof of concept study in Subsection III-B and the concept of the DF described in Subsection III-A show, that the real-world implementation inevitably differs from the simplified model, in this case the optimization problem of the DF. In the following, we elaborate factors leading to this deviation and identify potential research questions that need to be addressed for the real-world implementation. Thereby, we divide the factors into two categories, namely hardware and software.

Starting with the hardware side, we divide the components according to the concept of the DF in the flexible and inflexible components as well as additional hardware required to implement the DF.

With respect to the inflexible components, the factors and their corresponding research questions are:

- Efficiency factor/loss coefficient η: This factor is used in the BESS model to describe how the power input of the BESS is translated into its SoE. As this factor depends on

other factors such as the temperature and the age of the BESS, it is not constant and therefore another uncertainty. What is the impact of this simplified model in real-world and does the model need to be more detailed?
- State of Energy: Because of the aging of the BESS and other influences, it is difficult to estimate the real SoE which is needed for the optimization problem. Which approach for estimating the SoE should be used?
- Flexibilities in power: In which range can the flexible components provide as well as active as reactive power for fulfilling the schedule?
- Response behavior of the flexible component: How fast are the flexible components reacting on a change in setpoint and are there different ways in which they are reacting, like ramping up the power to the desired setpoint? This could constrain the ability to use the flexible component to hold a specific setpoint. How much does the response behavior of different hardware components influence the use of the flexibility of the components and how has the optimization problem to be adapted?
- Continuous power vs. peak power: Most BESSs can deliver more power over a short period of time until they reduce the power to a level they can hold over a long period of time. This ability can help in case of sudden peaks of the inflexible prosumers. Can the short-term flexibility boost of components help to meet the schedule and how can it be integrated into the optimization problem?

Regarding inflexible components, there are other questions in the implementation that should be investigated:

- Phase imbalances of prosumers: A lot of household devices are only attached to one phase which can burden the distribution grid. For example, some EVs charge after a while only on phase 1 with a high load. Therefore, it is important to balance the usage over all phases.
- High gradients of prosumers: The output power of e.g. solar cells highly depends on the irradiance which can suddenly change, causing high gradients. Therefore, one needs to consider how high gradients need to be addressed.

Furthermore, on the hardware side, it has to be considered that in addition to the basic components of the DF additional hardware is needed, that affects the system. For example, several measurement devices with different temporal resolutions have to be installed for the real-world implementation of the DF.

On the software side, the following research questions need to be addressed:

- Technical restrictions: Due to communication protocols and the structure of the communication setup, delays and synchronization problems must be taken into account. There can also be restrictions on how often a component accepts setpoints, for example, due to physical properties that make control difficult.
- Regulations by law: Regarding the data collected for better forecasting and controlling the components, the limitations for data security have to be taken into account.

Finally, if the concept of the DF is implemented in real-world, further questions regarding the ancillary objective of the DF can be considered:

- Can the concept of the DF also be adapted to reactive power and could it be used for providing necessary reactive power to the grid?
- Can the concept of the DF also help to guarantee voltage stability in a street of houses?

D. Requirements for the experimental research infrastructure

In order to investigate the research questions described in Subsection III-C regarding the real-world implementation of the theoretical concept, there are several requirements for a suitable experimental research infrastructure. These requirements can be split into three main categories and will be described in detail in the following section.

a) Required components and controllability of components: All components should be fully controllable so that the schedule-based control strategies can be used. This leads to the following requirements:

- Possibility of decentralized and central control of individual components, as well as control of the entire complex,
- Usage of the typically used protocols in automation technology like MQTT, UDP, TCP/IP, OCPP, etc., and
- Reproducibility in control of the components.

b) Data acquisition and evaluability: For an adaptable experimental research infrastructure in terms of usability for different schedule-based control strategies, we need to record the voltages and currents of all phases directly at the used components and at the different intersection points in the household grid. Derived by the raw values of the currents and voltages all other relevant variables such as active or reactive power, phase angles, and even harmonics can be derived. The measurements must also have a feasible resolution so that all relevant variables, such as harmonics, which may result from the use of inverters, can also be detected. Furthermore, the measurements have to be synchronized so that both the reference of the measured data for control and the subsequent evaluation is clear. Additionally, all data has to be stored for evaluation.

c) Experimental research infrastructure: The experimental research infrastructure should represent a typical residential building including renewable energy sources such as PV systems. As a typical residential building is connected to a low-voltage distribution grid the experimental research infrastructure should be able to interact with other distribution grid participants, such as other buildings or even wind power plants. Moreover, the distribution grid should be able to operate at different grid states and to apply for example load steps on the building to investigate how it acts on sudden changes.

E. Experimental research infrastructure

To explore schedule-based control strategies like the DF, we present an experimental research infrastructure with three identical experimental buildings [20]. The buildings fulfill the requirements of Subsection III-D and are operated by the automation system of the Energy Lab 2.0 [19], so that the experiments are reproducible. The experimental buildings are connected to the busbar matrix of the Energy Lab 2.0 in order to emulate different grid states. The overall concept of the Energy Lab 2.0 is presented in [21], [22].

The schematic representation of the experimental research infrastructure is shown in Figure 4. On the left-hand side, the setup of the experimental grid is depicted. To this experimental grid we can connect a normal $400\,\mathrm{V}$ low-voltage distribution grid fed by the public $20\,\mathrm{kV}$ grid or we can simulate a low-voltage distribution grid by integrating a synchronous machine. Moreover, we can also integrate a Power-Hardware-in-the-Loop (PHiL) system to connect the building for example to a low inertia grid. As the experimental grid is galvanically separated from the public grid, we are also able to set untypical states of the grid, such as changing the frequency in a range of $45\,\mathrm{Hz}$ to $65\,\mathrm{Hz}$. Additionally, we can implement high load steps to investigate if the attached components are able to stabilize the grid. The adaptable busbar matrix allows the free configuration of topologies in the buildings and in the connected distribution grid. This makes it easy to add further buildings to consider the interactions between the buildings. To record all necessary data, the building is equipped with numerous measurement devices that record voltage and current with $20\,\mathrm{kHz}$ sampling rate. All devices are synchronized by NTP or if necessary PTP.

On the right-hand side in Figure 4, one of the three experimental buildings is connected to the busbar matrix. All three experimental buildings are equipped with flexible and inflexible components, see the list below. Thereby, we refer to components that can be either flexible or inflexible as adaptable flexible, or inflexible.

- Flexible components:
  - BESS of the shelf. Standard communication interface: $19.5\,\mathrm{kWh}$ capacity
- Inflexible components:
  - Solar cells: 30 x $320\,\mathrm{Wp}$, in total $9.6\,\mathrm{kWp}$
  - Non-controllable typical building loads
- Adaptable flexible or inflexible components:
  - Electrical car
  - Heat pump
  - Controllable typical building loads

With these components, different scenarios can be integrated.

In summary, the proposed experimental research infrastructure can be used to investigate the research questions identified in Subsection III-C arising from the real-world implementation of the DF. In comparison to [3], [9], [10], it takes into account the high dynamics of small residential buildings with high PV power generation and their impact on the low-voltage distribution grid acting as a feeder. This investigation can be extended both in terms of the experimental grid and the buildings and their components considered.

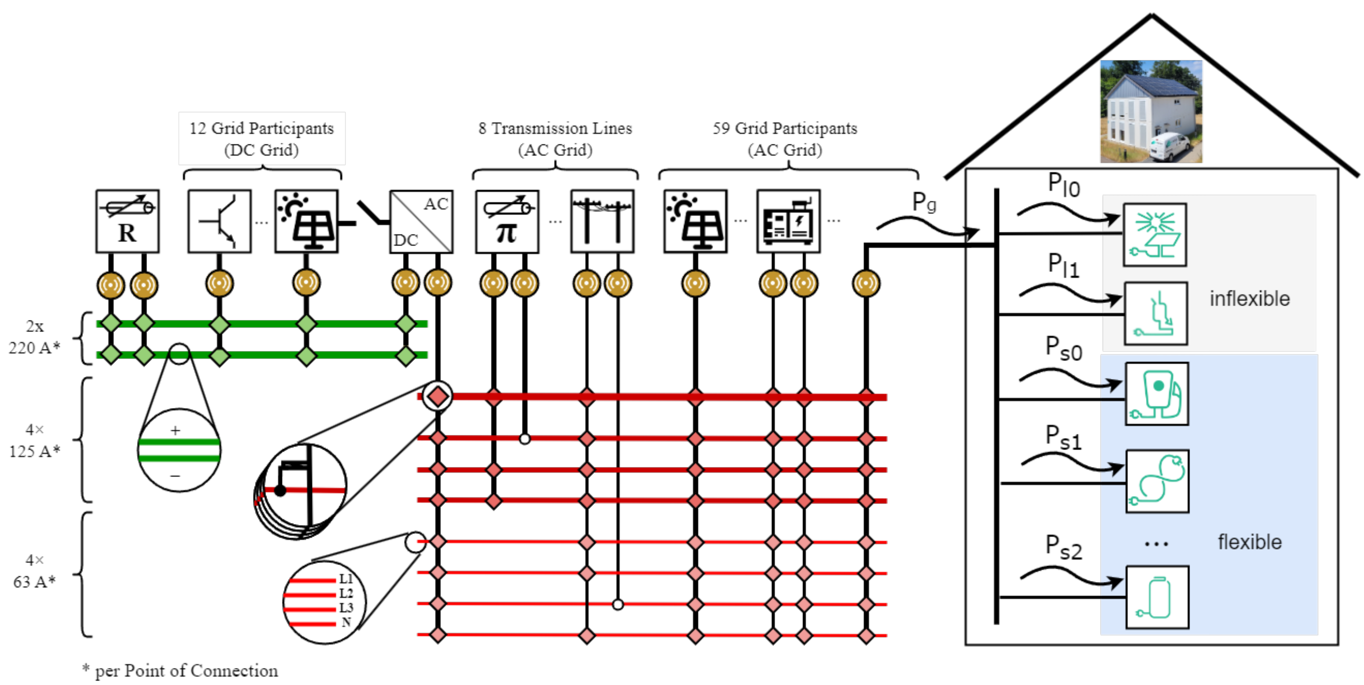

Fig. 4: Structure of the proposed experimental infrastructure (adapted from [19])

IV. Conclusion

The present paper considers the real-world implementation of a schedule-based control system known as dispatchable feeder. More precisely, we elaborate on research questions that need to be addressed with the real-world implementation of the concept at the low-voltage distribution level with respect to hardware and software. Furthermore, we introduce an experimental research infrastructure for this real-world implementation of the dispatchable feeder. This proposed infrastructure meets the requirements of the hardware components and their controllability and the needed data. It aims to systematically evaluate the real-world usage of schedule-based control systems at low-voltage distribution level.

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Author Contributions

Author contributions according to Contributor Roles Taxonomy (CRediT, https://www.casrai.org/credit.html): *Conceptualization:* S.B., M.B., D.W., J.G., F.W., R.M.; *Software:* S.B., M.B., V.W., C.H.; *Validation:* S.B., M.B., V.W., C.H.; *Investigation:* S.B., M.B., V.W., C.H.; *Writing - original draft:* S.B., M.B., D.W., J.G.; *Writing - review and editing:* S.B., M.B., D.W., J.G., V.W., C.H., F.W., R.M., S.W., V.H.; *Visualization:* S.B., M.B., D.W., S.W.; *Supervision:* R.M., V.H.; *Funding acquisition:* V.H.

References

[1] "Verordnung des Umweltministeriums zu den Pflichten zur Installation von Photovoltaikanlagen auf Dach- und Parkplatzflächen (Photovoltaik-Pflicht-Verordnung - PVPf-VO)," Jan. 2022.

[2] Sozialdemokratische Partei Deutschlands (SPD),, BÜNDNIS 90 / DIE GRÜNEN, and Freien Demokraten (FDP), "Koalitionsvertrag 2021 – 2025 zwischen der Sozialdemokratischen Partei Deutschlands (SPD), BÜNDNIS 90 / DIE GRÜNEN und den Freien Demokraten (FDP)," 2021.

[3] F. Sossan, E. Namor, R. Cherkaoui, and M. Paolone, "Achieving the Dispatchability of Distribution Feeders Through Prosumers Data Driven Forecasting and Model Predictive Control of Electrochemical Storage," *IEEE Transactions on Sustainable Energy*, vol. 7, no. 4, pp. 1762–1777, Oct. 2016.

[4] R. R. Appino, J. González Ordiano, R. Mikut, T. Faulwasser, and V. Hagenmeyer, "On the use of probabilistic forecasts in scheduling of renewable energy sources coupled to storages," *Applied Energy*, vol. 210, pp. 1207–1218, Jan. 2018.

[5] D. Werling, B. Heidrich, H. K. Çakmak, and V. Hagenmeyer, "Towards line-restricted dispatchable feeders using probabilistic forecasts for PV-dominated low-voltage distribution grids," in *Proceedings of the Thirteenth ACM International Conference on Future Energy Systems*. Virtual Event: ACM, Jun. 2022, pp. 395–400.

[6] E. Stai, L. Reyes-Chamorro, F. Sossan, J.-Y. Le Boudec, and M. Paolone, "Dispatching Stochastic Heterogeneous Resources Accounting for Grid and Battery Losses," *IEEE Transactions on Smart Grid*, vol. 9, no. 6, pp. 6522–6539, Nov. 2018.

[7] Y. Zuo, Z. Yuan, F. Sossan, A. Zecchino, R. Cherkaoui, and M. Paolone, "Performance assessment of grid-forming and grid-following converter-interfaced battery energy storage systems on frequency regulation in low-inertia power grids," *Sustainable Energy, Grids and Networks*, vol. 27, p. 100496, Sep. 2021.

[8] U. Langenmayr, W. Wang, and P. Jochem, "Unit commitment of photovoltaic-battery systems: An advanced approach considering uncertainties from load, electric vehicles, and photovoltaic," *Applied Energy*, vol. 280, p. 115972, Dec. 2020.

[9] F. Sossan and M. Paolone, "Integration and Operation of Utility-Scale Battery Energy Storage Systems: the EPFL's Experience," *IFAC-PapersOnLine*, vol. 49, no. 27, pp. 433–438, 2016.

[10] E. Namor, F. Sossan, R. Cherkaoui, and M. Paolone, "Control of Battery Storage Systems for the Simultaneous Provision of Multiple Services," *IEEE Transactions on Smart Grid*, vol. 10, no. 3, pp. 2799–2808, May 2019.

[11] S. Ahmad, M. Shafiullah, C. B. Ahmed, and M. Alowaifeer, "A Review of Microgrid Energy Management and Control Strategies," *IEEE Access*, vol. 11, pp. 21 729–21 757, 2023.

[12] F. Etedadi, K. Agbossou, S. Kelouwani, N. F. Henao, and S. Hosseini, "Coordination of Smart Home Energy Management Systems in Neighborhood Areas: A Systematic Review," *IEEE Access*, vol. PP, pp. 1–1, Feb. 2021.

[13] I. Gomes, K. Bot, M. G. Ruano, and A. Ruano, "Recent Techniques Used in Home Energy Management Systems: A Review," *Energies*, vol. 15, no. 8, p. 2866, Jan. 2022, number: 8 Publisher: Multidisciplinary Digital Publishing Institute.

[14] S. Hussain, C. Z. El-Bayeh, C. Lai, and U. Eicker, "Multi-Level Energy Management Systems Toward a Smarter Grid: A Review," *IEEE Access*, vol. 9, pp. 71 994–72 016, 2021, conference Name: IEEE Access.

[15] N. Lidula and A. Rajapakse, "Microgrids research: A review of experimental microgrids and test systems," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 1, pp. 186–202, Jan. 2011.

[16] A. Bernstein, L. Reyes-Chamorro, J.-Y. Le Boudec, and M. Paolone, "A composable method for real-time control of active distribution networks with explicit power setpoints. Part I: Framework," *Electric Power Systems Research*, vol. 125, pp. 254–264, Aug. 2015.

[17] L. Reyes-Chamorro, A. Bernstein, J.-Y. Le Boudec, and M. Paolone, "A composable method for real-time control of active distribution networks with explicit power setpoints. Part II: Implementation and validation," *Electric Power Systems Research*, vol. 125, pp. 265–280, Aug. 2015.

[18] A. Benigni, A. Xhonneux, D. Carta, T. Pesch, and D. Muller, "On the development of control solutions for local energy communities: An incremental prototyping approach and related infrastructure," *at - Automatisierungstechnik*, vol. 70, no. 12, pp. 1095–1115, Dec. 2022.

[19] F. Wiegel, J. Wachter, M. Kyesswa, R. Mikut, S. Waczowicz, and V. Hagenmeyer, "Smart Energy System Control Laboratory – a fully-automated and user-oriented research infrastructure for controlling and operating smart energy systems," *at - Automatisierungstechnik*, vol. 70, no. 12, pp. 1116–1133, Dec. 2022.

[20] M. Frahm, P. Zwickel, J. Wachter, F. Langner, P. Strauch, J. Matthes, and V. Hagenmeyer, "Occupant-oriented economic model predictive control for demand response in buildings," in *Proceedings of the Thirteenth ACM International Conference on Future Energy Systems*. Virtual Event: ACM, Jun. 2022, pp. 354–360.

[21] V. Hagenmeyer, H. K. Cakmak, C. Düpmeier, T. Faulwasser, J. Isele, H. B. Keller, P. Kohlhepp, U. Kühnapfel, U. Stucky, S. Waczowicz, and R. Mikut, "Information and Communication Technology in Energy Lab 2.0: Smart Energies System Simulation and Control Center with an Open-Street-Map-Based Power Flow Simulation Example," *Energy Technology*, vol. 4, no. 1, pp. 145–162, Jan. 2016.

[22] B. Emonts, M. Müller, M. Hehemann, H. Janßen, R. Keller, M. Stähler, A. Stähler, V. Hagenmeyer, R. Dittmeyer, P. Pfeifer, S. Waczowicz, M. Rubin, N. Munzke, and S. Kasselmann, "A Holistic Consideration of Megawatt Electrolysis as a Key Component of Sector Coupling," *Energies*, vol. 15, no. 10, p. 3656, May 2022.