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Review

Assessing the Role of Energy Storage in Multiple Energy Carriers toward Providing Ancillary Services: A Review

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Abstract: Renewable energy power plants and transport and heating electrification projects are being deployed to enable the replacement of fossil fuels as the primary energy source. This transition encourages distributed generation but makes the grid more weather-dependent, thus reducing its inertia. Simultaneously, electrical network operators face voltage, frequency, and stability challenges at the distribution level. Networks were not designed to manage the stochasticity of renewable energy sources or the congestion caused by the new transport and heating demands. Such challenges are commonly addressed through infrastructure reinforcements. This review studies how energy storage systems with different carriers can provide a collaborative solution involving prosumers as ancillary services providers at the distribution level. We focused on the European urban context; thus, we analyzed renewable energy sources, batteries, supercapacitors, hydrogen fuel cells, thermal energy storage, and electric vehicles. A thorough review of successful implementations proved that including storage in one or more carriers benefits the distribution system operators and the prosumers, from both technical and economic perspectives. We propose a correlation between individual energy storage technologies and the ancillary services they can provide based on their responses to specific grid requirements. Therefore, distribution system operators can address network issues together with the prosumers. Nevertheless, attractive regulatory frameworks and business models are required to motivate prosumers to use their assets to support the grid. Further work is recommended to describe the joint operation of multiple storage technologies as multicarrier systems, focusing on the coupling of electrical and thermal energy storage. Additionally, how ancillary services affect the energy storage system's aging should be studied.

Keywords: ancillary services; battery energy storage; flexibility; multicarrier energy storage systems; thermal energy storage systems

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1. Introduction

As the global trend in energy is to displace fossil fuels as the primary source of electricity, transport, and heat production, alternatives such as renewable energy sources (RESs), electric vehicles (EVs), and heat pumps (HPs) are playing a significant role in the energy transition. Following the Renewable Energy Directive (2018/2001/EU), the power generation in the European Union has to achieve 32% from RESs by 2030 [1] (or eventually 40% if the proposal in [2] is approved), under the Regulations on the Internal Market for Electricity (2019/943/EU) [3]. However, a massive deployment of renewable energy sources distributed generators (DGs) without the integral participation of the stakeholders in the energy supply chain (see Figure 1) can cause a series of problems in the grid. Those problems are described in Section 2.

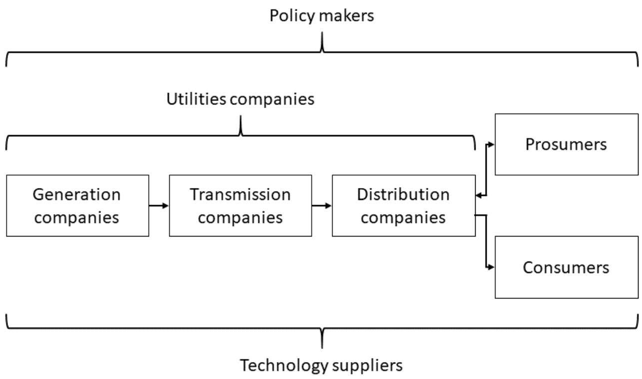


Figure 1. Energy market supply chain and stakeholders.

With the scheme presented in Figure 1, when installing RESs, the users are not only mere consumers but become prosumers actively participating in the energy exchange with the grid. This transition causes unprecedented alterations in the energy flux, as the effects of the DG are nonlinear concerning the penetration level [4,5]. Owing to the improvements in batteries' efficiency and reductions in price [6], electric vehicle sales are increasing and battery energy storage systems (BESSs) are more commonly installed together with RESs. The effects of energy storage systems (ESSs) on the grid still need to be investigated [7]; however, an appropriate deployment, combined with RES and EV in distribution networks, can improve the grid's performance, as well reduce the adverse effects of DGs on them [6–9].

Numerous projects studies been conducted to combine different assets such as RESs, BESSs, and EVs in various configurations, creating microgrids [10]. It is considered a smart grid when those microgrids react to the needs of the electrical network. A business case is needed to evaluate the feasibility of microgrids, as the conditions are different among countries or even cities within the same country. In [11], key performance indicators were proposed to validate the feasibility of deploying a smart grid in Greece under the context of the One Network for Europe (OneNet) project. Although the smart grids studied by [10] presented encouraging results, extrapolating them to different scales is not straightforward. Scalability, replicability, and interoperability are the main challenges to generalizing the results from a local experiment [12]. Therefore, researchers are working toward understanding the behavior of smart grids under different conditions to forecast their scaled outcomes [12].

Complementary to the electrical energy exchange, systems can participate in heat exchange and regulation [13]. This kind of multicarrier energy system (MCES) involves a transversal approach, considering the production and storage of electricity and heat, allowing the bidirectional flow of energy, and is open to including different technologies associated with each system component. As expected, the energy management systems (EMSs) face challenges regarding the control strategies, as they need to consider communication infrastructure [6,9], energy management algorithms [6,9], weather conditions forecast [9], and demand response predictions [14], to mention some.

Despite the challenges mentioned above, there is consensus in the literature that adding thermal energy storage systems (TESSs) provides a more integral approach to smart grids and cities. In this scenario, the prosumers collaborate with the distribution system operators (DSOs) through ancillary services to keep the grid operating in the most favorable conditions [15–20]. Therefore, the motivation of the present study was to investigate, through an exhaustive review, the ancillary services that a multicarrier energy storage systems (MCESSs) can provide to reduce the effect of DGs on the distribution grids. A selection of relevant reviews is presented in Table 1. As can be seen, previous reviews did not describe a correlation between MCES sand ancillary services, and a comprehensive study on the implementation of MCESSs as ancillary services providers has not been reported in the literature. The contributions of this study are: first, to determine the correlation between ESSs in different energy carriers with the ancillary services they can provide second, to identify potential benefits of using multicarrier energy systems. It was found that implementing energy storage systems from different carriers diversifies the ancillary services (i.e., the flexibility) prosumers can offer to the grid. The role of each subsystem is highlighted, and recent case studies are presented as evidence. However, further work is required to fully understand the behavior of more complex MCESSs to optimize the outcome.

Table 1. Findings and research gaps of recent reviews.

Main Topic	Major Findings	Research Gaps	Ref.
Challenges associated with smart grid implementations.	Identification of the main challenges to transforming the existing power network into a smart grid. ESSs can balance the supply and demand mismatch through ancillary services.	Aggregation of multiple ESSs in the low-voltage network. The effect of combined ESSs.	[21]
Capacity sizing methods, power converter topologies to interface multiple ESSs, architectures, control, and EMS to couple two or more ESSs.	When multiple ESS sare coupled, the trend is to couple a high-power storage system to meet transient power behavior and a high-energy storage system to supply energy in the long term. The most common combination of ESSs is BESSs with supercapacitors. Time delays between control layers affect the overall operation and stability.	Aggregation of multiple microgrids. Consider ancillary services. Inclusion of thermal energy systems. Multiobjective sizing methods for several coupled ESSs.	[22]
How EV chargers can provide ancillary services to system operators.	Classification of the ancillary services available. Identification of the ancillary services EV can provide to the DSO and TSO theoretically and which are on a commercial stage. Identification of the actors involved.	Ancillary services from other ESS than EV. Smart charging infrastructure to diversify the commercial stage ancillary services available.	[23]
The techno-economic and regulatory status of energy storage and power quality services at the distribution level.	Including RESs causes reluctance by the DSO, as they change their business models, generally seen as profit loss instead of new business opportunities. BESSs distributed in the grid will play a significant role in the implementation of RESs, but their deployment has to consider the total BESS life cycle. BESS can address grid issues through ancillary services as long as such services are appropriately recognized and rewarded by the DSO.	Quantification of the effects of deploying ESSs. The impact of combined ESSs. Aggregation of multiple ESSs in a low-voltage network.	[24]
Analysis of potential ancillary services for transmission level and distribution level networks.	Voltage control, congestion management, and peak shaving are the most suitable ancillary services at the distribution level. Primary frequency control, reactive power control, and peak shaving are more effective for the transmission level. Centralized and distributed ESSs are reliable alternatives for ensuring grid stability.	Considers the ESSs as assets of the DSO or TSO. Aggregation of multiple ESSs. Network equivalent models.	[25]
Coordination strategies of multiple microgrids in the distribution network.	Identification of aggregation strategies to provide ancillary services and market participation. Aggregated microgrids have the potential to facilitate the inclusion of RESs into the grid. Standardization for interconnection and interoperability to participate in the energy market. Standardization in cyber-security.	Considers the microgrids as assets of the DSO or TSO. Inclusion of thermal energy systems.	[26]
Planning and deployment of DGs and ESSs, including their barriers and technologies available for implementation.	Identification of recent planning and allocation strategies for DGs and ESSs. Identification of uncertainty modeling methods for DG and ESS planning.	Correlation of the ESS and the needs of the system operators. Considers the microgrids as assets of the DSO or TSO. Inclusion of thermal energy systems. Grid failure studies on the distribution level. Multiobjective sizing methods for ESS.	[27]

This paper is organized as follows: the main problem is analyzed in Section 2. Section 2.1 lists the main strategies to displace fossil fuels as the primary energy source; Section 2.2 details the main effects those strategies are having on the grid. The emerging solutions to address those effects are mentioned in Section 2.3. Section 3 explores the ancillary services prosumers can provide to the grid. As sources of integral solutions, multicarrier energy storage systems are detailed in Section 4. The results are discussed in Section 5, and Section 6 presents the main conclusions.

2. Problem Description

The CO_2 level in the atmosphere, among other greenhouse gases, has dramatically increased since the Industrial Revolution. Despite being hard to define, a point of no return is an already discussed threat [28]. In response, authorities worldwide have proposed strategies and policies toward the transition to RES, electric mobility, and, more recently, the electrification of heating systems to displace fossil fuels as the primary energy source, for instance, the Paris Agreement and Sustainable Development Goals 7 and 13 at the international level; most countries have set their own environmental goals [29]. Despite those efforts, by 2020, only 11.4% of global energy consumption was produced by renewable energies (6.4% hydro, 2.2% wind, and 1.1% solar) [30,31] (Individual metrics by country can also be found.). Unavoidably, some obstacles have appeared in the process, especially in urban areas due to reduced space, as shown in Figure 2, necessitating new solutions. We investigated multicarrier energy storage systems as possible sources of flexibility by supporting grid operators in urban areas through ancillary services.

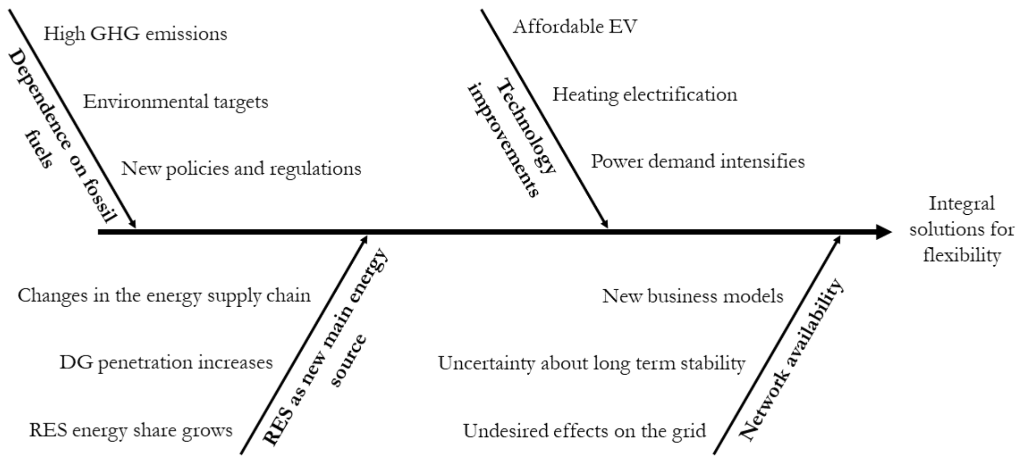


Figure 2. Causes and effects of the transition to RESs, resulting in the need for integral solutions.

2.1. Traditional Solutions to Displace Fossil Fuels

From the energy perspective, several strategies have been considered to mitigate the anthropogenic contribution to the greenhouse effect in the atmosphere. In 2018, the distribution of the global total energy consumption by final use was 51% thermal, 32% transport, and 17% power, whereas renewable energy supplied only 10.9% (5.2% thermal, 1.1% transport, and 4.6% power) [29]. Specific measures are considered per sector, highlighting RESs in power generation, electric mobility in transport, and heating electrification in heat production. This section presents the status and goals of the solutions implemented to displace fossil fuels as the primary energy source per sector.

2.1.1. Renewable Energy Sources

In the last two decades, the share of renewable energy sources has consistently increased yearly. Wind and solar installed power have increased notably when analyzing each source individually during the last decade. However, their contribution is still not comparable with other RES, such as hydropower or biomass. Nonetheless, this increasing trend might not be enough to accomplish Sustainable Development Goal 7 [32]. Cost-wise, PV and wind systems' deployment capital and operational expenses have decreased due to technological improvements, manufacturing processes, and incentives from tax authorities in multiple countries [33].

Both centralized plants and distributed generation have caused many challenges as RESs gained ground in the energy mix, which can be addressed with different energy storage strategies [34–36], but more studies are required. A significant challenge is that both PV and wind depend on mid- and long-term weather predictions, the variability in which is enhanced due to global warming. Furthermore, the datasets used to estimate the generation potential from renewable sources use historical measurements and different numerical models, which do not necessarily converge when compared [37]. This mismatch causes a proportional behavior between the increase in weather-dependent RESs and their deployment and integration complexity on the existing network.

2.1.2. Electric Mobility

In 2020, the transport sector consumed around 60% of the global oil demand [32]. However, electric vehicle (EV) sales are consistently rising as a measure to change the primary energy source for the sector from fossil fuels to electricity [38]. Three critical mitigation responses were proposed in [39] to reduce the transport CO_2 emissions: avoid and reduce the need for motorized travel, shift to more environmentally friendly transport modes, and improve the efficiency of transport modes, where electric mobility plays a key role. Regarding the last point, smart charging devices for EVs are constantly being developed by research groups worldwide, with approaches such as charging profiles [40], wireless charging [41], increasing the process efficiency [42], or decreasing the charging time [43], for instance, in the attempt to reduce the effects on the grid. The requirements for electrical mobility exceed the vehicles and their charging stations: urban planning must be considered and electric systems reinforced, as the demand will increase to meet the power requirements [44,45].

2.1.3. Heating Electrification

Given that more than half of the total final energy consumption is dedicated to heat-related processes, being only 10.2% from renewable sources [29], heating electrification is expected to play a significant role in the energy transition. Multiple authors agree on the potential of heat pumps (HPs) [46–48]; other technologies, such as heat pipes, are other promising alternatives to fossil fuel-based heating systems [49]. Three major techno-economical obstacles were analyzed in [50]. First, electricity is more expensive than fossil fuels, resulting in a less profitable solution unless distribution companies implement new utility tariffs or business models. Second, the nature of the local energy mix, i.e., If the primary energy source of the mix is already fossil-fuel-based, increasing the power demand will likely result in more greenhouse gas emissions, requiring more high-level solutions. Third, heat pumps consume more energy under very low temperatures due to the larger compression ratios, low heat production, and frosting, resulting in less attractiveness compared with conventional heating systems. Hence, integral solutions involving new products, optimization, and energy management and exchange systems are required.

2.2. Undesired Effects of Distributed Generation on the Grid

Grid managers need to be able to control the production and flow of energy among the transmission and distribution networks to ensure their stability. When energy sources are transitioned from controllable fossil fuel plants to RESs, numerous nonlinear phenomena manifest on the grid, as they were not designed for RESs or DGs. This section briefly presents the counterproductive effects DGs (mainly PV) causes on the network. Table 2 presents a list of reported issues.

Table 2. Reported unexpected outcomes on grids due unplanned DG deployment.

Phenomenon	Detail	Proposed Solution	Ref.
Loss of inertia and frequency shifts	The effect of different levels of PV and wind in Jordan's national grid was analyzed, resulting in a penetration of over 40% that would compromise the frequency stability of the system due to a reduction in its inertia.	As a neighboring country, the interconnection with Egypt can support the system.	[51]
Voltage issues	Circuits operate at, or near, their limits for the connection of any further DG in southwest England.	High-voltage network reinforcement.	[52]
Voltage issues	Overvoltage surpasses the 110% limit in rural low-voltage grid in Portugal, given the low load required near the injection point, forcing an intermittent connection of the inverter to the grid.		[53]
Voltage issues	Voltage fluctuation due to grid congestion produced by generator start-ups to supply the demand planned to be met by wind farms in Germany.	Export of excess power to neighboring countries.	[54]
Power curtailment and grid congestion	Increase in installed PV and wind systems in Italy caused grid congestion and power curtailment.	Development of a smart grid and use of dynamic line rating to reduce the power curtailment levels from 1% to 2%.	[54]
Power curtailment and grid congestion	The German regulations give DGs priority access to the grid infrastructure, which, added to the single price zone electric market, created severe grid congestion, resulting in 4.7 TWh curtailed due to feed-in management in 2015.	Development and implementation of a congestion management strategy on the distribution level to provide flexibility as an alternative to power curtailment.	[55]
Power curtailment	Power curtailment in China of 17.1% in wind and 10% in solar during 2016.	Enhance consumption near the injection point, implement subsidies and feed-in tariffs, and ultra-high-voltage (UHV) transmission.	[56]
Uncertainty of long-term effects	Islanded systems, such as Crete and Cyprus, would be more affected by the massive deployment of RESs due to their stochasticity.	The interconnection of Greece (Attica Crete), Cyprus, and Israel allows high penetration of RESs while providing a secure match between demand and supply, reducing the need for fossil-fuel-based plants.	[57]
Uncertainty of long-term effects	By 2011, The Netherlands implemented several policies to ensure the network infrastructure could support the incoming power plants to supply the increasing demand, creating uncertainty for the transmission system operators regarding the grid's costs and the market's behavior.		[58]
Utility rate variations	A study about the reaction of the electrical utility market related to the mass implementation of DGs in Brazil demonstrated that utility companies need a solid framework to regulate the DGs, as their advantages still need to be fully understood.	Implement strategies and models to understand the effect of DGs at the micro and mini level to implement more efficient utilities.	[59]

2.2.1. Grid Congestion

A fundamental disadvantage of PV and wind power as energy sources compared with fossil fuels is their inherent dependency on weather conditions (e.g., solar irradiance, temperature, and wind speed), causing stochastic behavior of the instantaneous output power. Due to their noncontrollable nature, the bigger the share of PV or wind in the energy mix, the less inertia the network will have, as inertia comes from the kinetic energy of rotating generators [60]. Sudden variations in local weather conditions can cause disturbances in energy production, increasing the probabilities of power swings due to the weakened frequency response and reducing the reliability of the power supply quality. At the same time, the seasonal variability in the PV systems is significant (especially in higher latitudes): a property that can intensify the mismatch between the demand profile and the PV generation curve, even under clear-sky conditions.

2.2.2. Overvoltage

The traditional electrical grid infrastructure was designed to have a central power injection point, which the grid operator can regulate. However, distributed generation can lead to excessive power flowing through the low-voltage lines, causing reverse flow, thus increasing the system voltage [61,62]. Unbalances between the lines can also cause overvoltage [61,63]. In [64], it was found that low-power (6 kW) single-phase PV inverters could cause voltage variations of up to 2% in low-voltage networks (higher values are unlikely, yet not impossible). Others [65] concluded that overvoltage is the dominant effect when defining the PV penetration limit on low-voltage systems. DSO relies on thermal generators to address overvoltage, diminishing the reduction in GHG emissions achieved by deploying RESs as distributed generators. As thermal generators will deprecate due to environmental goals, DSO need to find alternatives to compensate for the power imbalances [66].

2.2.3. Underused Capacity Due to Power Curtailment

Increasing the RES share in the energy mix is intended to reduce CO_2 emissions; however, [67] evidenced that it is a misconception that maximizing RESs without considering their effect on the whole energy system always lowers CO_2 emissions. PV and wind power plants usually need to be overdimensioned to counteract the weather variability [68]; thus, power needs to be curtailed, resulting in lost energy and frequency shifts. Multiple research groups have studied this effect and proposed strategies to exploit the curtailed power, including coordinated power compensation algorithms [69], battery storage [70], EV charge coordination [71], and introducing electric heaters and heat storage [72]. Nevertheless, the energy is either lost or traded with neighboring countries in most cases, requiring transmission network improvements [73].

2.2.4. Uncertainty in Long-Term Effects on Grid Stability

The stability of the grid is one of the biggest concerns for grid managers. They require information on how the demand changes over time and how they can control the production in real time to address sudden power fluctuations and avoid causing problems for the prosumers, consumers, and the network. With environmental targets, such as the Paris Agreement or Sustainable Development Goal 7, renewable energy distributed generation incorporates stochastic energy production and distribution behaviors. Additionally, the electrification of heating and the consistent growth in EV penetration make the production vs. demand comparison forecasts more complex. According to [29], between 2017 and 2018, there was a 63% increase in the global number of electric passenger cars; moreover, the usage of RESs in heating, ventilation, and air conditioning (HVAC) supplied around 10% of the energy; yet, there has been slow progress in policy support.

2.2.5. Utility Rate Variation

Distributed energy resources also consistently affect the profile of electricity prices [5]. As explained by [74], the current trend is transitioning from dependent customers to more independent prosumers. To cover the energy purchase reduction, as the utility's cost does not accordingly decrease, the rates will increase, encouraging consumers to transition and urging new utility business models compatible with the distributed generation scheme. At the same time, current regulations are required to establish the framework for those new business models. These regulations are designed to minimize the risk instead of creating synergies between the parts of the energy supply chain [75,76]. The current policies are mostly net metering and feed-in tariffs, which successfully stimulate decentralized generation but might cause mid- and long-term problems, as they need to consider the effects of DGs on the grid [77]. For that reason, new policies should focus on establishing energy-sharing guidelines and allow full participation of disadvantaged and vulnerable communities [78].

2.3. Emerging Solutions

Multiple strategies have been proposed to overcome the energy transition challenges produced by RESs and DGs in electrical networks, as shown in Table 2. We focused on how energy storage systems from different carriers can provide flexibility through ancillary services in urban areas, as is discussed in Sections 3 and 4. Although we focused on the technical perspective, regulatory solutions are also being developed to modernize the policy frameworks.

From the technical perspective, the solutions found in the literature can be classified into two different yet mutually dependent groups. The first is energy modeling and control strategies for energy management systems (EMSs). These strategies aim to maximize the usage of the network's infrastructure while minimizing losses and adverse effects. A comparison of different optimization strategies used in microgrids worldwide is presented in [79], classifying the methods as deterministic, metaheuristic, artificial intelligence, or others, providing insights into their best applications. The second, developing or upgrading existing devices to execute the energy management algorithms, such as ESSs, converters, and other novel devices, is equally important.

A progressive regulatory framework is also required for a successful transition. Such frameworks include policies designed for more dynamic energy flow and consider all the parts in the value chain, avoiding governance barriers to adequate RES project deployment [78,80]. In this context, multiple strategies have constantly been proposed, including new utility models more suitable for the new generation scheme [81] and incentives that encourage prosumers to participate in energy exchange [77]. From the policymakers' perspective, [66] mentioned the most relevant codes for electricity markets in Europe, referred to as the Target Model, which includes: the EU Directives 2009/72/EC, 2019/944, and 2019/943, and the EU Commission Regulations 2017/2195, 2017/1485, 2015/1222, and 2016/1719. Additionally, technical standards are continuously being developed and adjusted worldwide, aiming to establish the operating parameters to be used in the regulations intended to minimize adverse effects on the network, such as UL 1741 [82], IEEE 519 [83], IEC 61727 [84], and EN 50160 [85]. From boh the policy and technical perspectives, the responsibility of stability control is assigned to the transmission system operators.

Despite previous efforts to establish working frameworks, they tended to be monodisciplinary. For example, the Smart Grids Architecture Model framework, developed by the European Telecommunications Standards Institute, the European Committee for Electrotechnical Standardization, and the European Committee for Standardization, exclusively addresses the technical components, ignoring the social aspects [86]. What is more, the energy market has barriers related to uncertainty about the performance of the RESs, the effect of DGs and ESSs on electrical networks, privacy policies, and the lack of incentives for prosumers, among others [66,87,88]. Consequently, numerous smart grid projects prematurely fail [89]. Some authors, such as [11,90], mentioned that the new business models should compensate storage system owners based on the imbalances they can cover, either individually or aggregated, as well as the eventually accelerated aging caused by supporting the grid. For instance, the results in [90] showed a return on investment between 9.5 and 19.1 years when BESSs are deployed to provide frequency balancing in the Italian wholesale market, which might not be attractive to investors, as the expected life of a BESS is between 5 and 15 years.

3. Ancillary Services

As early as 2008, Ref. [91] recommended a proactive DG transition, allowing grid operators to take advantage of the systems to increase the network's performance. However, as pointed out in [92], and following what is presented in Table 2, most of the challenges are currently solved by reinforcing the infrastructure to handle the new power sources or exporting the energy to neighboring countries (which usually requires infrastructure improvement). Instead, actively including the DG system assets in energy exchange, especially as BESSs and EVs are more commonly included within DG systems, can also be a solution. Multiple authors [92–96] recommended more flexible electric systems oriented toward cooperative energy exchange business models, exploiting the DG systems as ancillary services providers. This section details the primary ancillary services of distributed systems with electric energy storage systems that can be provided to the grid (Note that the inclusion of BESSs with RESs in DGs is not dependent on all of the studied ancillary services, meaning that some of them do not require BESSs, RESs, or both). We assumed that higher power and energy costs imply a higher operational cost. Therefore, grid operators desire that some consumers purchase power in a cheaper, lower-demand timeframe so the power demand is more evenly distributed throughout the day.

A summary of successful implementations and proofs of concept is shown in Table 3. The results demonstrate an increase in the power quality of the grid due to reductions in the rate of the change in frequency and voltage fluctuations, thus, in power losses. Nonetheless, new utility models are required to increase the profitability of ESS implementation. Likewise, some ancillary services can provide support when thermal systems are implemented. For instance, using TES to reduce the heat load at the community level (peak shaving) or controlling the head demand either controlled by an intelligent thermostat or through the direct control of heat pumps (demand response), reducing the fluctuation in temperature in both cases.

Table 3. Representative cases of reported outcomes of ancillary services through DG systems.

Ancillary Service	Detail	Results	Ref.
Reactive power control	Simulation using the IEEE 9-bus system, considering synchronous generators and a cluster of coherent grid-following DGs under different control strategies.	Controlled power converters enhanced the network performance, reducing the rate of change of frequency.	[97]
Reactive power control	Simulation of a Newcastle, Australia, rural network using a 33-node network with 11 loads on medium voltage, with data collected on PV generation, loads, and network voltage from trial sites.	Reduction of curtailment loss and overvoltage.	[98]
Energy arbitrage	Multiple scenarios were studied in the Belfast City Hospital, Northern Ireland, using different BESS and PV combinations and dimensions to provide grid services and energy arbitrage.	BESS is not economically viable for arbitrage alone, but it is if income from other ancillary services is included. Revenue increases with the increase in the BESS power.	[99]
Peak shaving	A peak shaving strategy with different BESS sizes was implemented on a test house, representative of a typical house in Northern Ireland, without considering the heating consumption in the measurements.	The peaks were reduced to less than 5%of their initial magnitude and duration and avoided between 70% and 90% of the energy exports. The system is hardly viable with flat tariffs, but incentive tariffs would result in profit.	[100]
Peak shaving	The economic feasibility of a water tank thermal energy storage system connected to district heating and a heat recovery system in Trondheim, Norway, was tested after implementing a thermal peak-shaving strategy.	The system was able to shave up to 39% of the thermal load and increase waste heat self-use 27%, resulting in 9% savings on annual heating costs.	[101]
Frequency balancing	A combination of a BESSs and supercapacitors is proposed to provide enhanced frequency response in the U.K. market, considering the minimum required capacity for each ESS and proposing a power management strategy based on allocating the power so that the SoC of the BESS remains near a reference value.	Incorporating the supercapacitor reduced about20% the usage of the BESS, and the power management strategy reduced the variation in the SoC of the BESS.	[102]
Frequency balancing	Simulation using the IEEE 33-bus system and historical data from the Australian Energy Market Operator, considering the BESS provides frequency control services with a per-use-share rental strategy.	The strategy was proven as economically viable and reliable.	[103]
Voltage control	A 21-node system within a 3.09 km line was simulated, including households, an office building, a school, and a store, studying the effect of BESS, EV, and home energy storage systems.	An adequate combination of EV, BESS, and home energy storage systems consistently reduced the voltage fluctuation at the end of the line.	[104]
Voltage control	The North Cyprus power system (132 kV on transmission and 66 kV subtransmission, 49 busbars, 60 transmission lines, a Y-connected capacitive filter, 432 MW of power plants, and 2.27 MW of DG) was studied to analyze if DGs can improve the voltage profile in the network.	If the DG locations are chosen correctly, the system can operate within safe limits with a penetration level of 50%, achieving a 36.5% reduction in active power loss.	[105]

Table 3. *Cont.*

Ancillary Service	Detail	Results	Ref.
Congestion management	A congestion management algorithm was tested in the H2020 InterFlex demonstrator in The Netherlands (26 EV charging points of 22 kW, a 250 kW/315 kWh BESS, and a 260 kWp PV system that supplies 350 apartments through two 630 kVA transformers), based on the loss of life of a transformer and the DSO's financial risk of a blackout due to overloading.	The algorithm successfully predicts the load pattern, allowing a decision-making model to monetize the required flexibility.	[106]
Demand response	Three villages in Portugal clustered the consumers with similar consumption patterns and implemented a demand response strategy.	Reduction in the household energy bill.	[107]
Demand response	A home energy management system was combined with a smart thermostat to control household-power-shiftable loads, including BESSs and EVs, under Turkey's time-of-use and feed-in tariff rates.	A reduction of 53.2% on the daily costs was achieved under Turkey's time-of-use and feed-in tariff rates.	[108]
Demand response	A TESS was implemented to reduce the required cycles of an air source heat pump.	The fluctuation in the outlet water temperature was reduced, while the unit decreased the number of on–off operations.	[109]
Direct load management	A home energy management system (HEMS) was implemented in a single-family villas category in Riyadh, Saudi Arabia, aiming to achieve a net zero energy home.	Reduction in the household energy consumption by 37% compared with the energy use index in ASHRAE 100-2015, modifying the luminance level and the HVAC load.	[110]

3.1. Reactive Power Control

Section 2.2 mentioned that the uncontrolled injection of active power in the grid causes voltage increases, leading to undesired overvoltage. The DSO is responsible for ensuring voltage stability. Currently, network operators use thermal generators to compensate for power fluctuations; however, due to environmental goals, such plants will be decommissioned in the short and mid term, requiring for new sources of reactive power control [66]. Reactive power handling can balance this effect. Modern inverters can independently control active and reactive power under the inverter-allowed apparent power, increasing the RES hosting capacity of the local network [111,112]. Reactive power control can more than merely compensate for the effect of RES active power injection on the grid. DSOs may use the reactive power supply from distributed generators to ensure voltage quality of the network at lower voltages than thermal generators, typically used at high voltage levels [112]. Nevertheless, the IEEE Standard 1547 does not allow any inverter interconnected with the grid to adjust its voltage using reactive power compensation [113]. Therefore, DG cannot provide reactive power compensation, thus, forcing the DSO to invest in alternatives instead of considering collaborative solutions.

3.2. Energy Arbitrage

The power demand on the grid is not constant over time; yet, it usually has a periodic pattern during the day, with expected peaks that depend on the circuit needs [114]. For that reason, DSOs usually have dynamic tariffs, where power and energy are more expensive during high-demand or peak hours [115]. From a financial approach, consuming energy when it is cheaper would result in a cost reduction opportunity. However, consumption mostly depends on activities; thus, moving the consumption periods outside the peak hours is only sometimes an option. Given that, BESSs can provide a profitable solution. The energy can be purchased when it is cheaper and used when it is more expensive without affecting daily activities, as demonstrated by [116]. From the grid perspective, it also reduces the grid's congestion because the demand increases in low-consumption periods and decreases during high-consumption periods, decreasing the demand gap during the day.

3.3. Peak Shaving

Similar to the energy arbitrage modus operandi, peak shaving can reduce the building's power peaks consumed from the grid during high-demand intervals. Under this scheme, however, the intention is to reduce the costs related to power instead of energy (which would eventually occur, depending on the utility model) [117]. From the grid perspective, the effects are similar. However, as the intention is to flatten the power consumed from the grid, it reduces its variability. Peak shaving allows a smoother energy exchange, preventing reverse current flow and voltage rise [117]. Multiple approaches have been applied in the literature to achieve this effect, considering the power source and implementation scale. A summary of the state-of-the-art methods can be found in [118].

3.4. Frequency Balancing

Traditionally, electric systems were designed for bulk-power plants with synchronous generators. On the other hand, RESs, more specifically variable renewable generation (e.g., wind or PV), are primarily inverter-based nonsynchronous energy sources. For that reason, increasing their share in the energy mix can lead to a more significant rate of change in the frequency and frequency deviations [119]. Nevertheless, modern inverters have frequency management functions that, when combined with a BESS, contribute to the network to reduce frequency deviations even further than conventional generation, due to their faster power response [120], building the concept of virtual inertia [121].

3.5. Voltage Control

erratic voltage behavior caused by an unevenly distributed high penetration of RESs on the grid is a significant challenge. Grid administrators have developed and implemented different control strategies to mitigate this effect to fulfill interconnection and power quality standards [122], such as IEEE 1547 [113] or ANSI C84.1 [123], respectively. However, the inclusion of BESSs can mitigate the volatility in the power flow, as demonstrated by [124]. The energy produced by power peaks can be stored and consumed or injected back into the grid. Hence, DGs with BESSs can provide inertia to the grid regarding voltage variations, if coordinated.

3.6. Congestion Management

When multiple distributed energy sources are included in the network, uncertainty in the energy flow is included in the system, creating congestion issues at the transmission level [125]. BESSs can manage the congestion in transmission lines to inject, store, or consume energy based on local or global network requirements, conducting the power flow [25,125]. Thus, if RESs and BESSs are coordinated in a smart grid, energy can be managed following local demand, reducing the congestion in the power lines at higher levels.

3.7. Demand Response Management

If the utility tariffs are known beforehand, the end-users can adapt their consumption as a response according to changes in the power and energy costs; this behavior is defined as demand response management [126]. In this context, demand response algorithms commonly choose the heating and air conditioning loads. HVAC systems are often controllable loads that can be manipulated owing to the thermal inertia in rooms and flexible temperature setpoints. As long as comfort is not compromised, especially in high-latitude countries, they represent a significant share of urban energy consumption [127,128]. Furthermore, demand management can be beneficial not only for the consumers from the economic perspective but for DSOs from a technical perspective; the power demand during peak hours decreases, and the load behavior supports the grid in maintaining the frequency after power swings [126,129].

3.8. Direct Load Management

As shown in [126], some authors considered direct load management as a category of demand response management. The difference is that direct load management algorithms modify the load in real time to meet the smart grid requirements, optimizing the energy consumed by specific loads as much as possible, and not only responding as pricing changes in energy. Consequently, the loads to be managed should be flexible enough, and some studies recommend HVAC, heat pumps, and EV as preferred considering their impact on the instantaneous power consumption [130,131]. Likewise, the Internet of things (IoT) and smart meters were also considered [132].

4. Multicarrier Energy Storage Systems

In Section 3, electric ancillary services were studied; however, heating systems can provide similar services under specific energy system architectures. Multicarrier energy systems are multiple-input, multiple-output systems that combine different energy types, such as thermal and electrical, as shown in Figure 3. An optimized MCES obtains better performance than when each system works individually. Considering the complexity of the MCES, we analyzed only the storage elements, as the contribution focuses on the ancillary services that multicarrier energy storage systems can provide as part of an MCES. Therefore, Section 4.1 mentions the main strategies to model MCESs. In Section 4.2, multiple ESSs are proposed as possible elements of a multicarrier energy storage system. Section 4.3 provides an overview of the state of the art of combined storage systems as part of MCESs.

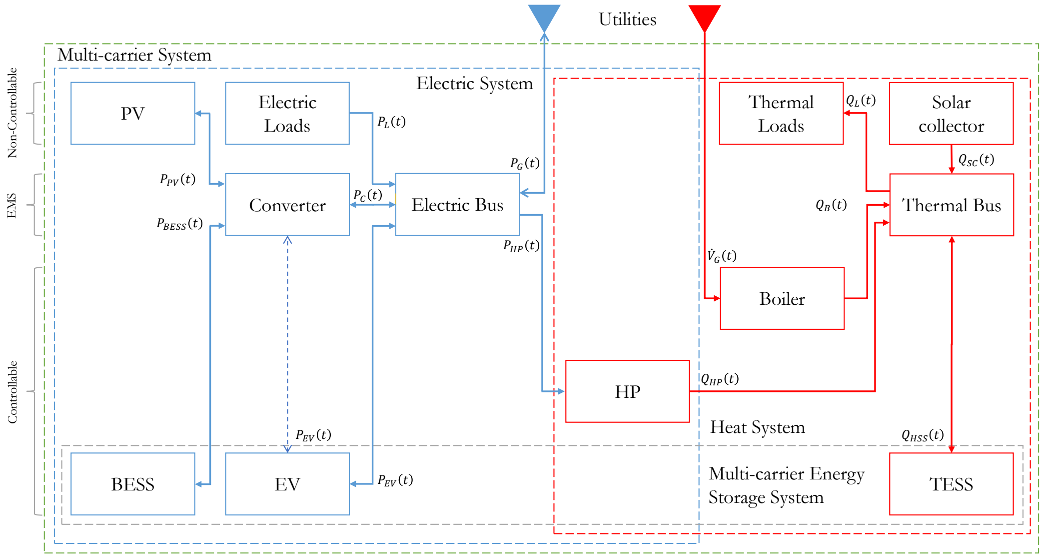


Figure 3. Schematic of the energy flow of a multicarrier energy storage system, where P_{PV} represents the instantaneous power produced by the PV system, P_{BESS} represents the instantaneous power provided/consumed by the BESS, P_C represents the instantaneous power provided/consumed by the converter, P_{EV} represents the instantaneous power provided/consumed by the EV converter (in some topologies, the EV charger is directly connected to the main converter; in others, the charger is connected to the electric bus), P_{HP} represents the instantaneous power consumed by the HP, P_L represents the instantaneous power consumed by the electric loads, P_G represents the instantaneous power consumed from/delivered to the grid, Q_{SC} represents the instantaneous heat produced by the solar collectors, Q_{HP} represents the instantaneous heat produced by the heatpump, Q_{TESS} represents the instantaneous heat provided/consumed by the TESS, Q_B represents the instantaneous heat produced by the boiler, Q_L represents the instantaneous heat consumed by the thermal loads, and $\dot{V}_G$ represents the instantaneous flow of gas consumed from the grid.

4.1. Mathematical Modeling of Multicarrier Energy Systems

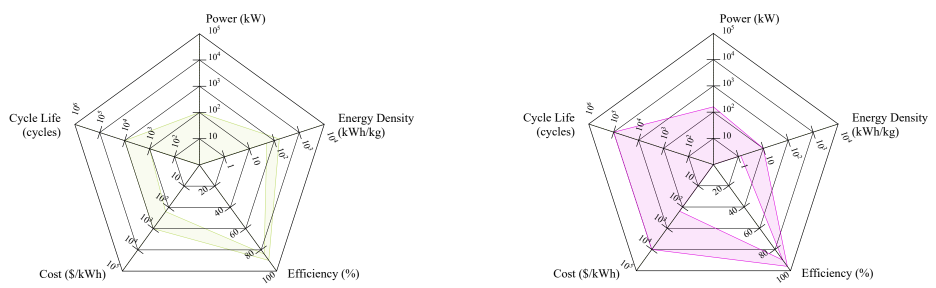
Describing the behavior of multicarrier energy systems depends on the correlation between each energy system considered in the designed topology and its components. For instance, a simplified schematic is presented in Figure 3, where the energy flows among the chosen devices are indicated. MCESs can provide suitable frameworks to combine electrical and thermal ancillary services if adequately implemented. Additional elements can be added to achieve the desired topology, e.g., wind systems, biofuel systems, cooling systems, supercapacitors (SCs), or hydrogen fuel cells. Because of the complexity, multiple modeling approaches have been proposed in the literature to overcome the challenge of simulating complex MCESs, including graph-based [133], port-Hamiltonian [134], probabilistic [135], stochastic [136], and information gap decision theory [137].

4.2. Elements in Multicarrier Energy Storage Systems

Considering the different requirements, a synergic combination of various ESSs would provide a more extensive range of possible ancillary services, as each ESS has individual applications. ESSs provide crucial support to the transmission system operators (TSOs) and distribution system operators during blackouts. This section considers electric, thermal, and chemical storage devices and electric vehicles (note that electric vehicles can behave as both a storage device and a controllable electrical load, according to the EMS algorithm).

Mechanical energy storage systems, particularly pumped storage hydropower (PSH), are promising solutions. As a mature technology, PSH has the highest installed capacity worldwide. Its most common applications are short- and long-term energy management, back-up, and black start [24]. Nevertheless, it is geographically limited and requires extensive environmental studies and permits, making it challenging to locally implement PSH in urban areas [138]. As we focused on European urban environments, we did not include them in the present review; however, the advantages of mechanical energy storage are described in [24,138].

Multiple key performance indicators (KPIs) are available to compare different ESS technologies. To compare technologies independent of the application, the most common KPIs are: the cost per unit of energy, the number of cycles (life), power range, energy density, and efficiency. For specific applications, one can use the levelized cost of storage (LCOS), as it depends on the number of cycles per year, the depth of discharge, and the discharge duration. Figure 4 shows a comparison summary of the studied elements, where the performance ranges for the main attributes are presented. Figure 5 depicts the energy availability, response times, and power ranges for the ESSs we considered within our scope. Although we did not extensively cover PSH in this work, we included it in Figure 5 as a comparison point for the other ESSs, given its relevance and suitability to provide ancillary services when it can be incorporated into the grid. For both figures, the literature survey was performed using general searching terms. The references were selected based on citation metrics (number of citations of the paper and rank of the journal), date of publication, and consistency with other publications.



(**a**) (**b**)

Figure 4. *Cont.*

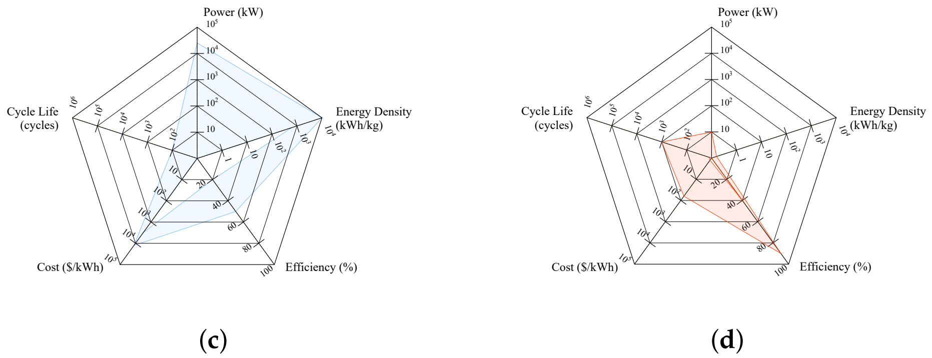


Figure 4. Comparison of the reported performance of the main attributes of different energy storage systems. The colored area represents the range between the best- and worst-case scenario reported in the literature per attribute. Note that the increases in the graphs are on a logarithmic scale in all attributes but the efficiency. (**a**) Reported performance of Li-ion batteries [126,139,140]. (**b**) Reported performance of supercapacitors [126,139,140]. (**c**) Reported performance of hydrogen fuel cells [126,139,140]. (**d**) Reported performance of thermal energy storage [140–144]. The power on this graph represents the heat transfer rate.

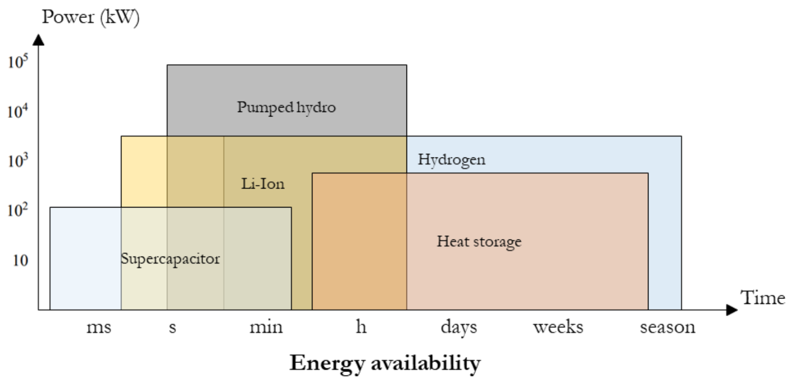


Figure 5. Comparison of the reported available power and energy, starting from the reaction time, of different energy storage systems [138,139,145].

4.2.1. Battery Energy Storage Systems

Battery energy systems store energy based on an electrochemical process. Multiple chemistries have been developed to enhance their performance, increasing the energy density and decreasing costs, including lead-acid, nickel-metal hydrate, and lithium-based [146]. Traditionally, lead-acid batteries were used as a backup in electrical systems. However, in the last decade, the prices of lithium-based batteries have dramatically decreased, which, added to their superior performance, has allowed more complex and reliable uses for the batteries [147]. A comprehensive review on the integration of BESSs into distribution systems was conducted by [6], including a comparison of the three main technologies of Li-ion BESSs. Table 4 presents a comparison of the best and worst performance found for different metrics per technology

The energy storage market includes other technologies, such as flow batteries (highlighting chemistries based on vanadium [148], but also zinc, iron, copper, and halides [149]), and salt batteries (e.g., sodium-sulfur [150], sodium-nickel-chloride [151], and sea-salt [152]). However, some of those batteries are still in early stages or development (e.g., flow batteries not based on vanadium and the sea-salt battery). On the other hand, some mature technologies are incompatible with the urban requirements despite having advantages over the lithium-based BESSs that can be used in other contexts. For instance, vanadium-based flow battery cost per energy unit is about one-third of that of lithium technologies [153], but its energy density is almost one order of magnitude lower [154], making it unsuitable for applications where high energy densities are required. Molten-salts batteries, such as sodium-sulfur and sodium-nickel-chloride, have energy densities similar to those of lithium-based technologies but operate at temperatures above 100 °C and up to 400 °C, which raises hazards and risk concerns [155]. Although some advances in such technologies working at room temperature have been achieved, there are challenges associated with lifetime and capacity fading [156].

Table 4. Performance ranges for lithium iron phosphate (LFP), lithium nickel manganese cobalt (NMC), and lithium nickel aluminum cobalt (NCA) BESSs [6,157].

	LFP	NMC	NCA
Energy density (Wh/kg)	75–190	120–200	140–240
Power density (W/kg)	200–1600	600–2400	600–700
Cell efficiency (%)	88–90	94–95	94–95
Cost (USD/Wh)	300–600	300–600	300–600
Lifetime (cycles)	5000–10,000	500–4000	500–3000

4.2.2. Supercapacitors

Capacitors are well-known devices that store energy through electric fields, reacting as a low-pass filter with short reaction times. Despite having low energy density, supercapacitors have high power density, short charge/discharge cycles, and long life [158,159]. Given those characteristics, supercapacitors are suitable for high-power, low-energy peaks, providing availability during voltage dips or short interruptions [139].

4.2.3. Thermal Energy Storage Systems

In Section 2, we mentioned that a significant share of energy in the mix is dedicated to producing heat, primarily from fossil fuels. Modern alternatives are under constant development to produce heat from electricity (building the concept of power-to-heat) or based on the thermal properties of different materials [160]. On the other hand, heat sources have long transient responses, leading to slow reaction times and energy loss. To overcome this challenge, authors [161,162] have mentioned the need for thermal energy storage to optimize the cycles of the heat energy source. Hence, Ref. [162] highlighted the importance of thermal energy storage when flexibility is considered. In [141], thermal energy storage systems were categorized as: active, when the system stores energy through a fluid that can flow between reservoirs; passive, when the energy storage medium is solid.

4.2.4. Hydrogen Fuel Cells

A hydrogen fuel cell (HFC) is a device that transforms the chemical energy from the reduction-oxidation reaction of a constant inflow of hydrogen and oxygen into electrical energy. This process occurs in an electrolyte, according to which the fuel cell can be categorized as alkaline, proton exchange membrane, phosphoric acid, molten carbonate, or solid oxide [163]. HFCs are combined with electrolyzers to produce and store hydrogen. However, the expected lifetime of an HFC is around 5 to 15 years [140], and its roundtrip efficiency is around 20–35%, both of which are lower than those of other ESS technologies [164]. The reason is that the overall efficiency includes the fuel cell efficiency (40–60%) [165] and the electrolyzer efficiency (40–60%) [166]. Efficiencies near 45% were reported but under specific conditions [167]. Additionally, the EMS requires robust control strategies to coordinate the HFC and electrolyzer [168], especially if the goal is to minimize the grid's impact or provide ancillary services. At the same time, the heat produced by the fuel cell can be transferred to a thermal load or storage, but further research is still required [169,170].

4.2.5. Electric Vehicles

In Section 2.1, electric mobility was mentioned as a suitable alternative for fossil fuels in transport. In this context, multiple approaches regarding the relationship between the electrical grid and electric vehicles have been proposed to minimize the effect of the increasing power demand to supply the energy required to charge the batteries in the EV. The EV chargers' power depends on the charging level (Power for levels 3 and 4 depends on the chargers' characteristics, but can easily surpass 100 kW [171,172].): between 3.7 kW (16 A per phase) for level 1 to 22 kW (32 A per phase) for level 2 [173]. When connected to the charger, the energy between the grid and the EV can flow from the grid to the EV (G2V) or from the EV to the grid (V2G) [174], following the EMS instructions. However, estimating the optimal power to whether charge or discharge the battery is a difficult task if the goal is to simultaneously minimize the charging time and the effect of the charger on the grid, as not enough data are currently available to make informed decisions in real time [175–177]. Another critical point to consider is the batteries' life cycle as an inherent consequence of the electrification of transport based on batteries. The potential of a second life for those batteries can be considered for stationary uses, as studied in [178].

4.3. Current Status on Combined Energy Storage Systems

In Section 4.2, energy storage systems were presented, and numerous combinations can be obtained to face different challenges, as reported in Table 5. This section analyzes the results of combining two or more of the previous systems, indicating the advantages and individual contributions to the overall result.

The combination of BESSs and supercapacitors connected to a PV installation was studied by [179–181], where their compatibility was demonstrated regarding reaction times, power, and energy supply. The supercapacitor smooths the short, high-power peaks in this arrangement, whereas the battery supplies power during longer intervals. This effect has multiple advantages in electrical systems that can be obtained through different topologies. An individual converter for the supercapacitor and the BESS produced better results, as the voltage in the DC line does not directly affect each storage device's voltages [180,181].

Supercapacitors were also studied with hydrogen fuel cells (including electrolyzers), commonly using the supercapacitor as an auxiliary source to compensate transient events [182–184], using different topologies, according to the application. For instance, Ref. [183] utilized supercapacitors as a secondary power source in a fuel cell system to protect it against sudden variations in current, increasing the life of the fuel cell. A hybrid converter for electric vehicles, using a proton exchange membrane fuel cell and supercapacitor, was proposed by [184]. Fuel cells and supercapacitors were also combined with wind energy [185] and PV [186] to supply fast variations in the load power that the fuel cell cannot.

To minimize the curtailments of RESs, Ref. [187] developed a deep learning algorithm to optimally size and operate an alkaline water electrolyzer and a BESS. The results showed a decrease of 97% in the curtailed power, with a return on investment shorter than five years. In [188], multiple microgrids (with an HFC, electrolyzer, BESS, and PV) were studied while working in parallel in a low-voltage AC system, using a constant reference inverse droop control method to solve the problem of the impedance differences. Their results showed an improvement in the power distribution and the response speed when the load suddenly changed.

Electric vehicles actively participate in energy exchange; therefore, the chargers' operation must be optimized to avoid significant effects on the grid. Including a BESS provides a solution, creating a demand response scheme, which controls the chargers' high load, as proposed in [189] and demonstrated in [190], where a 138% reduction in transformer overloading was achieved owing to an appropriate BESS size. Likewise, including an EV in a system can decrease the required size of the BESS to provide services to the grid [191], even when an HFC is also included as part of a hybrid energy storage system [192].

Thermal energy storage systems can also work alongside other energy storage systems. As demonstrated [193], an electric, thermal, and gas coupling was tested using the IEEE 18-bus distribution system, resulting in an energy-sharing scenario that allowed saving energy by sharing with other participants. In [194], BESS and TESS were simulated together to simplify the management of MG and enhance the BESS lifetime, increasing the BESS lifetime by 74% compared with that of a model that did not consider its aging. A more complex MCES was studied [195], where a combined heat and power microgrid was controlled through a mixed-integer linear programming-based energy management model on an MPC framework. The microgrid included a natural gas fuel cell, a boiler, a TESS, wind turbines, PV generators, and a BESS. The results showed an economic improvement regarding the system behavior when supplying electric and thermal loads; however, the thermal system was fossil-fuel-based.

Most of the literature is related to the behavior of electrical systems coupled together, with few implementations of TESs in comparison. The most common couple at the multicarrier level (electric and thermal systems) is through heat pumps. Based on the tolerance levels of the habitants of the studied buildings, heat pumps can provide flexibility to the network through ancillary services such as demand response and direct load control [196–198], without relying on thermal energy storage. Moreover, the TESs are primarily implemented at the community level [199–201]. Therefore, research on how multiple electrical and thermal storage devices couple would provide valuable insights into the energy transition, particularly at a lower level than communal systems.

Table 5. Reported implementations of ancillary services through multicarrier energy storage systems.

System Architecture	Detail	Results	Ref.
PV + BESS + TESS	Three load-shifting strategies were proposed to control an islanded multicarrier microgrid in Abu Dhabi, UAE, including demand response management.	The coordination of charge and discharge of the different ESSs, combined with PV regulation, allowed the implementation of demand response management, with cooling loads shifted due to the TESS and curtailed, if needed, to supply the power demand within the network.	[202]
PV + BESS + TESS + EV + CHP	A multicarrier energy system was tested with heat and electrical load data from a hospital in Okinawa, Japan, to minimize the annual costs while increasing the system's resilience.	The system successfully reduced the costs while providing a more resilient system against grid blackouts, regardless of the seasonal variability, and with an acceptable life cycle performance, also showing compatibility with demand response management.	[203]
PV + wind + concentrating solar power + BESS + TESS	The optimal capacities of BESS and TESS for a multicarrier energy system in north China were determined, considering curtailment and operative constraints.	The obtained capacities of BESS and TESS showed annual profits of USD 4.95 million, considering a generation price of 0.094 USD/kWh, with an annual curtailment rate lower than 5%.	[204]
PV + BESS + TESS	A study of BESS and TESS as sources of flexibility was performed in Victoria, Australia, considering cost minimization and electric self-sufficiency. The influence of electricity price signals was also taken into account.	The multicarrier energy system showed optimal results when the objective was cost reduction. Most of the revenue was from the PV + BESS coupling, given the thermal load considered, as it allowed energy arbitrage and demand response management. On the other hand, self-sufficiency did not show economic benefits or flexibility options.	[205]
PV + wind + diesel generation + BESS + TESS	To size the optimal BESS and TESS, data from a greenhouse with a microgrid in Iran were used to simulate an islanded condition in case of disconnection from the grid.	Once the microgrid was islanded, the BESS supported the frequency shifts. Moreover, the combination of BESS and TESS resulted in a reduction of 19% of the costs compared with only the BESS being implemented.	[206]
BESS + TESS + CHP + chiller + boiler + spinning reserve	An artificial neural network fed with data from a shopping mall in Bangkok, Thailand, was used to create a load forecast strategy that reduced the operative costs when implemented in a multicarrier energy system.	The numerical results showed a reduction of 12.52% in the total operating cost compared with a similar EMS without BESS and spinning reserve when implementing the direct load management strategy.	[207]

Table 5. *Cont.*

System Architecture	Detail	Results	Ref.
PV + BESS + solar heat exchanger + boiler	A residential area with centralized PV and solar heat exchangers was simulated using electrical, cooling, and thermal load data to study the effect of combining electrical and thermal storage to minimize the energy purchase costs. Constraints included energy balance, electricity price, capacity, and charge and discharge power of the BESS.	The results showed a 15% reduction in the total energy costs bought from the utilities due to the PV generation and energy arbitrage, without compromising the demand.	[208]
Photovoltaic–thermal + TESS	A centralized photovoltaic–thermal system combined with a community-level TESS was simulated for an energy network in The Netherlands to determine the optimal size of the TESS to reduce costs and CO_2 emissions when considering thermal, cooling, and electrical loads.	The results showed reductions in annual costs of between 10.5% and 31.9%, and in CO_2 emissions of between 14.9% and 47.8%, depending on the demand analyzed: heating, heating, and cooling, or heating, cooling, and electrical.	[209]

5. Discussion

Investments in RESs are growing worldwide to meet sustainability targets. Additionally, RES's versatility in the power range, increasing efficiency and reliability, and substantial cost reduction encourage those investments. Despite this, grid operators are not prepared for their large-scale effects. Large deployments result in adverse phenomena on the electrical network, creating uncertainties in voltage, frequency, and stability, as explained in Section 2.2 and summarized in Table 2. To address these challenges, the typical solutions require significant upgrades of the electrical systems' infrastructure, highlighting network reinforcements or energy trade, increasing costs, and reducing the revenue in the mid and long terms. Instead, cooperative schemes with the prosumers, who actively participate in the energy exchange, may add value if considered.

Simultaneously, the energy regulations were not initially designed to consider distributed generation, but the emerging policies encourage the usage of RESs. This misalignment results in governance barriers to the adequate deployment of RES projects, regardless of the power scale, because RES penetration is growing faster than the regulatory framework is developing. Especially at the distribution level, DG intensifies the technical challenges, given the stochasticity of the energy flow, and the energy market is affected. The price is updated almost in real time, urging new, progressive, and more flexible business models in the supply chain. Furthermore, strategies promote the electrification of heating and transport, increasing the power demand but decreasing the predictability of its behavior. The result is an even more complex power flow in an already congested network.

Energy storage can become the core of the energy transition if prosumers and DSOs collaborate through ancillary services. Numerous successful implementations of ancillary services can be found in the literature. In Table 3, we provide a representative list. After analyzing those cases, we found that including ESSs within the distributed generators reduces the voltage and frequency effects caused on the grid by the RESs, therefore enhancing the outcome of DG, as the ESSs provide the inertia RES undersupply to the grid (voltage control and frequency balancing). Furthermore, when ESSs are included in the DG systems, it is possible to provide support if an EMS controls the power flow according to the network requirements. There are three ways the DG system can support the grid: it can control its power factor to control the reactive power consumed or injected (reactive power control), reduce the power demanded from the grid at a particular moment (peak shaving, congestion management, demand response, and direct load management), as well as bidirectionally regulate the energy exchange with the grid (energy arbitrage). Depending on their nature, different energy storage devices can provide different services to the grid. However, combining their advantages into a more robust system is possible when working together in a multicarrier energy storage system. Nonetheless, increasing the number of ESSs in MCESSs involves more complex requirements for modeling and simulation, especially if multiple energy carriers are considered.

At the multicarrier level, the state-of-the-art literature highlights MCESSs as a promising alternative for prosumers to become ancillary services providers [210]. Although more studies on the behavior of electrical and thermal storage systems interaction are still required to fully understand their joint operation, the results shown in Table 5 support the hypothesis that the coupling between them would allow better control of the system's overall behavior. Considering that heating systems are required, it is safe to assume that the system is affected by seasonal variations. The time frames with a more significant need for heat coincide with the months with less PV availability. Therefore, under those conditions, options such as TESS and HFC can support the electrical system to provide heat without considerably increasing the power demand during cold seasons (it is considered an electrical source of heat, such as a heat pump.). According to the EMS, when the generation surpasses the consumption, energy can be stored in a BESS if required in the short term or used to produce thermal energy and hydrogen for long-term storage [168]. At the same time, if the surplus power produced by the DG is locally consumed through an electrolyzer, through a heat pump, or stored in a BESS, there will be less congestion on the network, as the energy injected into the grid can be coordinated according with the grid requirements.

It would be compelling to analyze how MCESS can provide ancillary services and, therefore, flexibility to the grid. In this regard, Table 5 presents a summary of recent studies of how multicarrier energy storage systems can contribute to diminishing the impact of DGs on electrical networks. The results suggest that energy arbitrage can be combined with demand response management or direct load control. The charge of BESSs or TESSs can be scheduled to purchase the energy during cheaper timeframes as an energy arbitrage strategy. At the same time, the power used to charge the ESSs during those timeframes can vary, in response to the congestion with demand response and direct load control strategies, to reduce their contribution to the grid congestion. Peak shaving can also be used with energy arbitrage or congestion management. Unlike demand response control or direct load control, peak shaving uses ESSs to smooth the peak without translating it to another moment. Thus, if the energy is purchased during a cheap timeframe and adequately scheduled for peak shaving, the amount of energy might not change, but its costs will be reduced as will power demand costs.

The main components of an MCESS are described in Table 6 with the ancillary services described in Section 3. The categorization is based on the successful implementations reported in the literature, considering the power and energy requirements and the energy management required to provide each ancillary service.

As expected, the ancillary services with common operation goals share the required subsystem on the MCES. Reactive power control, frequency balancing, and voltage control take advantage of the inverter's adjustable power factor and power output, allowing it to provide power during a shortage or inject reactive power in case of unbalances between phases [60], explaining why the RESs are required. Energy storage devices such as BESSs or HFCs can also achieve these functions, but it is less likely that their capacity would be big enough to create an impact. On the other hand, peak shaving and energy arbitrage are intended to regulate the power and energy purchased from the grid, respectively, requiring the store of energy. Thus, BESSs play a significant role, as their energy density–price ratio and reaction time makes them more affordable than HFCs, and as the energy is stored, it does not depend on weather conditions, as it does in RESs. Supercapacitors can also considerably contribute to peak shaving due to their power density. However, their lower energy density makes them unsuitable for operation beyond minutes. EVs can also provide support. Nevertheless, transportation is the primary goal of the energy stored in their batteries; therefore, a robust EMS strategy is required to ensure they will be reasonably charged when the user unplugs them from their charging stations without creating disturbances in the system.

Table 6. Role of the elements in a multicarrier energy system when providing ancillary services.

Issues	RES	Energy Storage Systems				EV	HP
		BESS	SC	HFC [1]	TESS		
Voltage issues	Reactive power control, voltage control	Congestion management					
Power curtailment	Energy arbitrage	Energy arbitrage		Energy arbitrage		Energy arbitrage	
Loss of inertia	Frequency balancing	Frequency balancing, congestion management		Frequency balancing, congestion management			
Rate variation		Energy arbitrage, demand response management, peak shaving	Peak shaving	Energy arbitrage, demand response management, direct load control, peak shaving	Demand response management, peak shaving	Energy arbitrage, demand response management, direct load control, peak shaving	Demand response management, direct load control
Grid congestion		Congestion management, demand response management, peak shaving	Peak shaving	Congestion management, demand response management, direct load control, peak shaving	Demand response management, peak shaving	Demand response management, direct load control, peak shaving	Demand response management, direct load control

[1] Including an electrolyzer.

From the thermal perspective, TESS is indispensable in assisting the heating system. TESSs can be used to reduce the energy purchased at a particular moment to generate heat (peak shaving) or to displace the purchase to more convenient timeframes (demand response management), independent of the heat source (e.g., boiler or heat pump). Due to the growing interest in electrifying heat production, energy conversion devices, such as heat pumps, must be considered part of the ancillary services. Such devices also must be included at the individual level, as most energy networks do not allow sharing of heat between buildings [209]. HFCs can also generate heat, but this is a side effect of the process needing improvement to be fully deployed. Furthermore, the implementation costs are a restriction for now.

Controlling the loads can also be beneficial for the grid, whether the control is based on the current state of the grid (direct load control) or trends (demand response management). The EMS orchestrates the power distribution and flows from the grid, loads, and ESSs. It is crucial to considering that the energy stored can be obtained from the grid. This consumption needs to be appropriately addressed, as the grid considers it a load. Charging EVs is also a task that should be coordinated, as mentioned before, due to the high power the charger can demand, making it a critical load to manage by the EMS if there is any EV connected to the system at a particular moment.

When considering the interaction of EVs and the grid, both G2V and V2G scenarios can provide flexibility. G2V can occur either at a constant rate or following a profile determined by the grid state in a smart grid behaving as a demand response [174]. Moreover, EV batteries can also be used as BESSs regarding ancillary services, as previously discussed, assuming the EMS is robust enough. For that reason, EVs can be a solution to reduce the size of BESSs in the scenario of reactive activity of the BESS (only works when there is energy consumption), as it is likely that the EV is at home at the same time the energy is consumed in a household. On the other hand, a more complex sizing methodology must be followed under more proactive activity.

Most of the literature reflects the main barriers described by [86]. Because there is uncertainty in both the amount of energy and power an MCESS can provide to the network and how the energy network will behave, new regulations are moving slowly. At the same time, this causes a reaction in the market, as the lack of regulations stops the DSO and TSO from proposing new business models to include DGs in the energy market as ancillary services providers, so it is attractive for prosumers to participate. In this regard, more research is needed to understand how the combined reaction of distributed MCESSs will affect the energy exchange between the DSO and the prosumers, as proposed by several authors [12,66,90], and the aging of the BESS [88]. In this way, innovative business models can be proposed to accelerate a collaborative energy transition.

Accurate models to predict DG power production are crucial for their adequate inclusion on the distribution grid to provide ancillary services. Multiple challenges must be faced to obtain a reliable estimation of the RES potential [211] and to optimally allocate the power when including storage [212,213]. Different approaches can be considered to forecast the meteorological resources used by RESs. For instance, Ref. [214] classified the forecasting models as meteorological, statistical, AI-based, and hybrid (combination of multiple models). The first two were traditionally used before more robust AI-based models were computationally possible. It was found that individual AI models had accuracies of around 10%, whereas hybrid models achieved accuracies near 5% of error in exchange for more computational resources and more extensive datasets. When considering storage also, the computational cost substantially increases for both the sizing of the components [215] and control of the energy flow [212,213], especially if the system considers more than one type of storage [216,217].

It is noteworthy that accurate models to predict DG power production are crucial for their adequate inclusion in the distribution grid to provide ancillary services. Multiple challenges must be faced to obtain a reliable estimation of the RES potential and to optimally allocate the power when including storage. Different approaches can be considered to forecast the meteorological resources used by RESs.

6. Conclusions

We investigated how energy storage systems can minimize the adverse phenomena caused by DGs on the grid. Energy storage systems from different carriers were analyzed, identifying the ancillary services they can provide. The documented outcomes suggest that when ESSs provide ancillary services, the result is a more flexible and cooperative network. Finally, the state-of-the-art multicarrier energy storage systems were presented as a more robust solution to combine multiple ancillary services, maximizing their advantages.

It was highlighted that an increase in noninertial, weather-dependant RESs (such as PV and wind) alone would not be enough to keep track of the upcoming demand trend, especially as EVs and heating electrification become more common in households. However, adding multicarrier storage systems to the network (centralized, local, or distributed) is a promising solution to increase the flexibility the system requires to counteract their variability. Numerous cases of implementation of ancillary services using energy storage systems were mentioned and analyzed. We found that HFCs and BESSs can provide more ancillary services among the ESSs studied. Implementation costs and efficiency limit the first, whereas the second is limited to electric carriers. From the thermal perspective, TESSs and HPs can be combined to optimally produce and store thermal energy. In this sense, as the heat pump acts as an energy conversion device, it couples the thermal and electrical systems, thus expanding the opportunities to provide ancillary services.

Hence, flexibility is the core of successful DG deployments. A cooperative scheme where prosumers offer ancillary services to the DSOs may contribute to controlling the effects of DGs on the grid and achieving a more robust and resilient network. This scheme creates a win-win scenario for DSOs and prosumers, incentivizing the prosumers to support the grid in exchange for rates that allow them to recover their investments. The literature proves that implementing ancillary services with a single carrier can reduce costs. Furthermore, combining different carriers also allows more efficient energy usage, as it can conveniently be converted from one carrier to another.

Distribution system operators can use distributed generation and storage to address stability issues. Distributed systems owners would find such collaboration attractive if ancillary services are included in the regulatory framework and new tariffs are proposed for them to use their assets to support the grid. Among those services are reactive power control, frequency balancing, voltage control, and congestion management, as their effect is at the distribution lines level. On the other hand, energy arbitrage, peak shaving, demand response management, and direct load control focus on the amount and manner the user consumes power and energy. Their implementation can lead to economic advantages. However, it requires robust control algorithms for the EMS, especially when the number of elements increases, creating opportunities for further work to determine if the same system can provide multiple ancillary services or if there are mutually exclusive combinations.

Further work should be conducted to quantify the flexibility effects of the ancillary services provided by MCESSs in the distribution networks, as such indicators were not found. Models can be built to estimate them, and living laboratories can be implemented to validate their benefits and investigate their implementation into automatic generation control software at different scales, e.g., centralized or aggregated. Moreover, aggregation strategies are needed to coordinate individual MCESS owners to provide collective support to the distribution network. The results of such studies will be crucial for a multidisciplinary regulatory framework. Finally, new business models must be investigated to incorporate the ancillary services into the current energy market, establishing clear tariffs for those services. Additionally, the aging effects caused by providing ancillary services would provide insight for long-term studies.

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Abbreviations

The following abbreviations are used in this manuscript:

BESS	Battery Energy Storage System
CHP	Combined Heat and Power
DG	Distributed Generation
DR	Demand Response
DSO	Distribution System Operators
EMS	Energy Management Systems
ESS	Energy Storage Systems
EV	Electric Vehicle
G2V	Grid-to-vehicle
HFC	Hydrogen Fuel Cell
HP	Heat Pump
HVAC	Heating, Ventilation, and Air Conditioning
KPI	Key Performance Indicator
LCOS	Levelized Cost of Storage
MCES	Multicarrier Energy System
MCESS	Multicarrier Energy Storage System
PSH	Pumped Storage Hydro

RES	Renewable Energy Sources
SC	Supercapacitor
TESS	Thermal Energy Storage System
TSO	Transmission System Operators
V2G	Vehicle-to-Grid

References

1. *Directives Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources*; European Union: Brussels, Belgium, 2018.
2. *Proposal for a Directive of the European Parliament and of the Council Amending Directive (EU) 2018/2001 of the European Parliament and of the Council, Regulation (EU) 2018/1999 of the European Parliament and of the Council and Directive 98/70/EC of the European Parliament and of the Council as Regards the Promotion of Energy from Renewable Sources, and Repealing Council Directive (EU) 2015/652, 14 July 2021*; European Union: Brussels, Belgium, 2021.
3. *Regulation (EU) 2019/ 943 of the European Parliament and of the Council—of 5 June 2019—on the Internal Market for Electricity*; European Union: Brussels, Belgium, 2019.
4. Meesenburg, W.; Ommen, T.; Elmegaard, B. Dynamic exergoeconomic analysis of a heat pump system used for ancillary services in an integrated energy system. *Energy* **2018**, *152*, 154–165. https://doi.org/10.1016/j.energy.2018.03.093.
5. Schibuola, L.; Scarpa, M.; Tambani, C. Demand response management by means of heat pumps controlled via real time pricing. *Energy Build.* **2015**, *90*, 15–28. https://doi.org/10.1016/j.enbuild.2014.12.047.
6. Stecca, M.; Elizondo, L.R.; Soeiro, T.B.; Bauer, P.; Palensky, P. A comprehensive review of the integration of battery energy storage systems into distribution networks. *IEEE Open J. Ind. Electron. Soc.* **2020**, *1*, 46–65. https://doi.org/10.1109/OJIES.2020.2981832.
7. Das, C.K.; Bass, O.; Kothapalli, G.; Mahmoud, T.S.; Habibi, D. Overview of energy storage systems in distribution networks: Placement, sizing, operation, and power quality. *Renew. Sustain. Energy Rev.* **2018**, *91*, 1205–1230. https://doi.org/10.1016/j.rser.2018.03.068.
8. Hennessy, J.; Li, H.; Wallin, F.; Thorin, E. Flexibility in thermal grids: A review of short-term storage in district heating distribution networks. *Energy Procedia* **2019**, *158*, 2430–2434. https://doi.org/10.1016/j.egypro.2019.01.302.
9. Chapaloglou, S.; Nesiadis, A.; Atsonios, K.; Nikolopoulos, N.; Grammelis, P.; Carrera, A.; Camara, O. Microgrid energy management strategies assessment through coupled thermal-electric considerations. *Energy Convers. Manag.* **2021**, *228*. https://doi.org/10.1016/j.enconman.2020.113711.
10. Jiménez, M.; Onyeji, I.; Colta, A.; Papaioannou, I.; Mengolini, A.; Alecu, C.; Maschio, I. *Smart Grid Projects in Europe: Lessons Learned and Current Developments*; Joint Research Centre: Brussels, Belgium, 2012.
11. Sijakovic, N.; Terzic, A.; Fotis, G.; Mentis, I.; Zafeiropoulou, M.; Maris, T.I.; Zoulias, E.; Elias, C.; Ristic, V.; Vita, V. Active System Management Approach for Flexibility Services to the Greek Transmission and Distribution System. *Energies* **2022**, *15*, 6134. https://doi.org/10.3390/en15176134.
12. Fotis, G.; Dikeakos, C.; Zafeiropoulos, E.; Pappas, S.; Vita, V. Scalability and Replicability for Smart Grid Innovation Projects and the Improvement of Renewable Energy Sources Exploitation: The FLEXITRANSTORE Case. *Energies* **2022**, *15*, 4519. https://doi.org/10.3390/en15134519.
13. Mansoor, M.; Stadler, M.; Zellinger, M.; Lichtenegger, K.; Auer, H.; Cosic, A. Optimal planning of thermal energy systems in a microgrid with seasonal storage and piecewise affine cost functions. *Energy* **2021**, *215*, 119095. https://doi.org/10.1016/j.energy.2020.119095.
14. Baldi, S.; Karagevrekis, A.; Michailidis, I.T.; Kosmatopoulos, E.B. Joint energy demand and thermal comfort optimization in photovoltaic-equipped interconnected microgrids. *Energy Convers. Manag.* **2015**, *101*, 352–363. https://doi.org/10.1016/j.enconman.2015.05.049.
15. Aquino-Robles, J. A.; Fernández-Nava, C.; and Corona, L. G. Los Servicios Auxiliares en Redes de Distribución Eléctrica en Presencia de Gran Cantidad de Generación Fotovoltaica de Baja Potencia *Pist. Educ.* **2018**, *40*, 19–37.
16. Kohlhepp, P.; Harb, H.; Wolisz, H.; Waczowicz, S.; Müller, D.; Hagenmeyer, V. Large-scale grid integration of residential thermal energy storages as demand-side flexibility resource: A review of international field studies. *Renew. Sustain. Energy Rev.* **2019**, *101*, 527–547. https://doi.org/10.1016/j.rser.2018.09.045.
17. Hoang, A.T.; Pham, V.V.; Nguyen, X.P. Integrating renewable sources into energy system for smart city as a sagacious strategy toward clean and sustainable process. *J. Clean. Prod.* **2021**, *305*, 127161. https://doi.org/10.1016/j.jclepro.2021.127161.
18. Richter, M. German utilities and distributed PV: How to overcome barriers to business model innovation. *Renew. Energy* **2013**, *55*, 456–466. https://doi.org/10.1016/j.renene.2012.12.052.
19. Nillesen, P.; Pollitt, M.; Witteler, E. *New Utility Business Model: A Global View*; Elsevier Inc.: Amsterdam, The Netherlands, 2014; pp. 33–47. https://doi.org/10.1016/B978-0-12-800240-7.00002-3.
20. Agüero, J.R.; Khodaei, A. Roadmaps for the Utility of the Future. *Electr. J.* **2015**, *28*, 7–17. https://doi.org/10.1016/j.tej.2015.11.002.
21. Jayachandran, M.; Rao, K.P.; Gatla, R.K.; Kalaivani, C.; Kalaiarasy, C.; Logasabarirajan, C. Operational concerns and solutions in smart electricity distribution systems. *Util. Policy* **2022**, *74*, 101329. https://doi.org/10.1016/j.jup.2021.101329.
22. Hajiaghasi, S.; Salemnia, A.; Hamzeh, M. Hybrid energy storage system for microgrids applications: A review. *J. Energy Storage* **2019**, *21*, 543–570. https://doi.org/10.1016/j.est.2018.12.017.

23. Sevdari, K.; Calearo, L.; Andersen, P.B.; Marinelli, M. Ancillary services and electric vehicles: An overview from charging clusters and chargers technology perspectives. *Renew. Sustain. Energy Rev.* **2022**, *167*, 112666. https://doi.org/10.1016/j.rser.2022.112666.
24. McIlwaine, N.; Foley, A.M.; Morrow, D.J.; Kez, D.A.; Zhang, C.; Lu, X.; Best, R.J. A state-of-the-art techno-economic review of distributed and embedded energy storage for energy systems. *Energy* **2021**, *229*, 120461. https://doi.org/10.1016/j.energy.2021.120461.
25. Kryonidis, G.C.; Kontis, E.O.; Papadopoulos, T.A.; Pippi, K.D.; Nousdilis, A.I.; Barzegkar-Ntovom, G.A.; Boubaris, A.D.; Papanikolaou, N.P. Ancillary services in active distribution networks: A review of technological trends from operational and online analysis perspective. *Renew. Sustain. Energy Rev.* **2021**, *147*, 111198. https://doi.org/10.1016/j.rser.2021.111198.
26. Villanueva-Rosario, J.A.; Santos-García, F.; Aybar-Mejía, M.E.; Mendoza-Araya, P.; Molina-García, A. Coordinated ancillary services, market participation and communication of multimicrogrids: A review. *Appl. Energy* **2022**, *308*, 118332. https://doi.org/10.1016/j.apenergy.2021.118332.
27. Zhang, D.; Shafiullah, G.; Das, C.K.; Wong, K.W. A systematic review of optimal planning and deployment of distributed generation and energy storage systems in power networks. *J. Energy Storage* **2022**, *56*, 105937. https://doi.org/10.1016/j.est.2022.105937.
28. Hansen, J.; Sato, M.; Kharecha, P.; Beerling, D.; Berner, R.; Masson-Delmotte, V.; Pagani, M.; Raymo, M.; Royer, D.L.; Zachos, J.C. Target atmospheric CO2: Where should humanity aim? *Open Atmos. Sci. J.* **2008**, *2*, 217–231.
29. *Renewables 2021 Global Status Report*; Available online: https://www.ren21.net/wp-content/uploads/2019/05/GSR2021_Full_Report.pdf (accessed on 28 December 2022).
30. Ritchie, H.; Roser, M. Our World in Data. Available online: https://ourworldindata.org/energy-mix (accessed on 22 September 2022).
31. *The World Bank Indicators*; Available online: https://data.worldbank.org/indicator/EG.FEC.RNEW.ZS?view=chart (accessed on 22 September 2022)
32. *Tracking SDG7 A Joint Report of the Custodian Agencies*; Available online: https://www.irena.org/publications/2021/Jun/Tracking-SDG-7-2021 (accessed on 28 December 2022)
33. Henni, S.; Staudt, P.; Weinhardt, C. A sharing economy for residential communities with PV-coupled battery storage: Benefits, pricing and participant matching. *Appl. Energy* **2021**, *301*, 117351. https://doi.org/10.1016/j.apenergy.2021.117351.
34. Bandyopadhyay, S.; Qin, Z.; Ramirez-Elizondo, L.; Bauer, P. Comparison of Battery Technologies for DC Microgrids with Integrated PV. In Proceedings of the 2019 IEEE Third International Conference on DC Microgrids (ICDCM), Matsue, Japan, 20–23 May 2019; pp. 1–9. https://doi.org/10.1109/icdcm45535.2019.9232746.
35. Wagh, S.; Yu, Y.; Shekhar, A.; Mouli, G.R.C.; Bauer, P. Aggregated Impact of EV Charger Type and EV Penetration level in Improving PV Integration in Distribution Grids. In Proceedings of the 2021 IEEE Transportation Electrification Conference & Expo (ITEC), Chicago, IL, USA, 21–25 June 2021; pp. 595–600. https://doi.org/10.1109/ITEC51675.2021.9490054.
36. Jacob, R.; Belusko, M.; Liu, M.; Saman, W.; Bruno, F. Using renewables coupled with thermal energy storage to reduce natural gas consumption in higher temperature commercial/industrial applications. *Renew. Energy* **2019**, *131*, 1035–1046. https://doi.org/10.1016/j.renene.2018.07.085.
37. Kies, A.; Schyska, B.U.; Bilousova, M.; Sayed, O.E.; Jurasz, J.; Stoecker, H. Critical review of renewable generation datasets and their implications for European power system models. *Renew. Sustain. Energy Rev.* **2021**, *152*, 111614. https://doi.org/10.1016/j.rser.2021.111614.
38. IEA *Global EV Outlook 2021 Accelerating Ambitions Despite the Pandemic*; Available online: https://www.iea.org/reports/global-ev-outlook-2021 (accessed on 28 December 2022.)
39. Peet, K.; Gota, S.; Huizenga, C.; Medimorec, N.; Enriquez, A.; Yiu, A.; Verheul, B.; Dalkmann, H.; Cardama, M. *Transport and Climate Change Global Status Report 2018 Partnership on Sustainable, Low Carbon Transport (SLoCaT) SLoCaT Secretariat Team*; SLoCaT Secretariat Team: Brussels, Belgium, 2018.
40. Lyu, D.; Soeiro, T.B.; Bauer, P. Impacts of Different Charging Strategies on the Electric Vehicle Battery Charger Circuit Using Phase-Shift Full-Bridge Converter. In Proceedings of the 2021 IEEE 19th International Power Electronics and Motion Control Conference (PEMC), Gliwice, Poland, 25–29 April 2021; pp. 256–263. https://doi.org/10.1109/PEMC48073.2021.9432497.
41. Grazian, F.; Shi, W.; Soeiro, T.B.; Dong, J.; Bauer, P. Electric Vehicle Charging Based on Inductive Power Transfer Employing Variable Compensation Capacitance for Optimum Load Matching. In Proceedings of the IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society, Singapore, 18–21 October 2020; pp. 5262–5267. https://doi.org/10.1109/IECON43393.2020.9254920.
42. Al, T.M.; Lyu, D.; Soeiro, T.B.; Bauer, P. Design of a Wide Output Voltage Dual Active Bridge Converter as Power Electronics Building Block for the Fast Charging of Electric Vehicles. In Proceedings of the 2021 IEEE 19th International Power Electronics and Motion Control Conference (PEMC), Gliwice, Poland, 25–29 April 2021; pp. 89–96. https://doi.org/10.1109/PEMC48073.2021.9432516.
43. Riekerk, C.; Grazian, F.; Soeiro, T.B.; Dong, J.; Bauer, P. Study on Soft Start-Up and Shut-Down Methods for Wireless Power Transfer Systems for the Charging of Electric Vehicles. In Proceedings of the 2021 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW), San Diego, CA, USA, 1–4 June 2021. https://doi.org/10.1109/WoW51332.2021.9462867.
44. Yu, Y.; Shekhar, A.; Mouli, G.C.R.; Bauer, P.; Refa, N.; Bernards, R. Impact of Uncontrolled Charging with Mass Deployment of Electric Vehicles on Low Voltage Distribution Networks. In Proceedings of the 2020 IEEE Transportation Electrification Conference & Expo (ITEC), Chicago, IL, USA, 23–26 June 2020; pp. 766–772. https://doi.org/10.1109/ITEC48692.2020.9161574.

45. Wang, L.; Qin, Z.; Slangen, T.; Bauer, P.; van Wijk, T. Grid Impact of Electric Vehicle Fast Charging Stations: Trends, Standards, Issues and Mitigation Measures - An Overview. *IEEE Open J. Power Electron.* **2021**, *2*, 56–74. https://doi.org/10.1109/ojpel.2021.3054601.
46. Souza, R.D.; Casisi, M.; Micheli, D.; Reini, M. A review of small–medium combined heat and power (CHP) technologies and their role within the 100% renewable energy systems scenario. *Energies* **2021**, *14*, 5338. https://doi.org/10.3390/en14175338.
47. Calise, F.; D'Accadia, M.D.; Barletta, C.; Battaglia, V.; Pfeifer, A.; Duic, N. Detailed modelling of the deep decarbonisation scenarios with demand response technologies in the heating and cooling sector: A case study for Italy. *Energies* **2017**, *10*, 1535. https://doi.org/10.3390/en10101535.
48. Stanek, W.; Simla, T.; Gazda, W. Exergetic and thermo-ecological assessment of heat pump supported by electricity from renewable sources. *Renew. Energy* **2019**, *131*, 404–412. https://doi.org/10.1016/j.renene.2018.07.084.
49. Kılkış, B.; Çağlar, M.; Şengül, M. Energy Benefits of Heat Pipe Technology for Achieving 100% Renewable Heating and Cooling for Fifth-Generation, Low-Temperature District Heating Systems. *Energies* **2021**, *14*, 5398. https://doi.org/10.3390/en14175398.
50. Eguiarte, O.; Garrido-Marijuán, A.; de Agustín-Camacho, P.; del Portillo, L.; Romero-Amorrortu, A. Energy, environmental and economic analysis of air-to-air heat pumps as an alternative to heating electrification in Europe. *Energies* **2020**, *13*, 3939. https://doi.org/10.3390/en13153939.
51. Feilat, E.A.; Azzam, S.; Al-Salaymeh, A. Impact of large PV and wind power plants on voltage and frequency stability of Jordan's national grid. *Sustain. Cities Soc.* **2018**, *36*, 257–271. https://doi.org/10.1016/j.scs.2017.10.035.
52. Western Power Distribution. *Distributed Generation EHV Constraint Maps*; Available online: https://www.westernpower.co.uk/connections/generation/distributed-generation-ehv-constraint-maps.aspx (accessed on 18 July 2022).
53. Pinto, R.J.C.; Mariano, S.J.P.S.; Calado, M.D.R.A. Power quality experimental analysis on rural home grid-connected PV systems. *Int. J. Photoenergy* **2015**, *2015*, 791680. https://doi.org/10.1155/2015/791680.
54. Boshell, F.; Miranda, R.; Ratka, S. *Solutions to Integrate High Shares of Variable Renewable Energy (Report to the G20 Energy Transitions Working Group (ETWG))*; International Renewable Energy Agency: Masdar City, United Arab Emirates, 2019.
55. Schermeyer, H.; Vergara, C.; Fichtner, W. Renewable energy curtailment: A case study on today's and tomorrow's congestion management. *Energy Policy* **2018**, *112*, 427–436. https://doi.org/10.1016/j.enpol.2017.10.037.
56. Zhang, X.; Wang, J.X.; Cao, Z.; Shen, S.; Meng, S.; Fan, J.L. What is driving the remarkable decline of wind and solar power curtailment in China? Evidence from China and four typical provinces. *Renew. Energy* **2021**, *174*, 31–42. https://doi.org/10.1016/j.renene.2021.04.043.
57. Brinkerink, M.; Gallachóir, B.; Deane, P. A comprehensive review on the benefits and challenges of global power grids and intercontinental interconnectors. *Renew. Sustain. Energy Rev.* **2019**, *107*, 274–287. https://doi.org/10.1016/j.rser.2019.03.003.
58. van Blijswijk, M.J.; de Vries, L.J. Evaluating congestion management in the Dutch electricity transmission grid. *Energy Policy* **2012**, *51*, 916–926. https://doi.org/10.1016/j.enpol.2012.09.051.
59. Rosa, C.B.; Rigo, P.D.; Rediske, G.; Moccellin, A.P.; Mairesse Siluk, J.C.; Michels, L. How to measure organizational performance of distributed generation in electric utilities? The Brazilian case. *Renew. Energy* **2021**, *169*, 191–203. https://doi.org/10.1016/j.renene.2021.01.027.
60. Gandhi, O.; Kumar, D.S.; Rodríguez-Gallegos, C.D.; Srinivasan, D. Review of power system impacts at high PV penetration Part I: Factors limiting PV penetration. *Solar Energy* **2020**, *210*, 181–201. https://doi.org/10.1016/j.solener.2020.06.097.
61. Wang, L.; Yan, R.; Saha, T.K. Voltage regulation challenges with unbalanced PV integration in low voltage distribution systems and the corresponding solution. *Appl. Energy* **2019**, *256*, 113927. https://doi.org/10.1016/j.apenergy.2019.113927.
62. Hung, D.Q.; Mishra, Y. Impacts of Single-Phase PV Injection on Voltage Quality in 3-Phase 4-Wire Distribution Systems. In Proceedings of the 2018 IEEE Power & Energy Society General Meeting (PESGM), Portland, OR, USA, 5–10 August 2018; pp. 1–5. https://doi.org/10.1109/PESGM.2018.8585530.
63. Yaghoobi, J.; Islam, M.; Mithulananthan, N. Analytical approach to assess the loadability of unbalanced distribution grid with rooftop PV units. *Appl. Energy* **2018**, *211*, 358–367. https://doi.org/10.1016/j.apenergy.2017.11.030.
64. Schwanz, D.; Moller, F.; Ronnberg, S.K.; Meyer, J.; Bollen, M.H. Stochastic Assessment of Voltage Unbalance Due to Single-Phase-Connected Solar Power. *IEEE Trans. Power Deliv.* **2017**, *32*, 852–861. https://doi.org/10.1109/TPWRD.2016.2579680.
65. Torquato, R.; Salles, D.; Pereira, C.O.; Meira, P.C.M.; Freitas, W. A Comprehensive Assessment of PV Hosting Capacity on Low-Voltage Distribution Systems. *IEEE Trans. Power Deliv.* **2018**, *33*, 1002–1012. https://doi.org/10.1109/TPWRD.2018.2798707.
66. Zafeiropoulou, M.; Mentis, I.; Sijakovic, N.; Terzic, A.; Fotis, G.; Maris, T.I.; Vita, V.; Zoulias, E.; Ristic, V.; Ekonomou, L. Forecasting Transmission and Distribution System Flexibility Needs for Severe Weather Condition Resilience and Outage Management. *Appl. Sci.* **2022**, *12*, 7334. https://doi.org/10.3390/app12147334.
67. Morales-España, G.; Nycander, E.; Sijm, J. Reducing CO_2 emissions by curtailing renewables: Examples from optimal power system operation. *Energy Econ.* **2021**, *99*, 105277. https://doi.org/10.1016/j.eneco.2021.105277.
68. Vonsien, S.; Madlener, R. Economic modeling of the economic efficiency of Li-ion battery storage with a special focus on residential PV systems. *Energy Procedia* **2019**, *158*, 3964–3975. https://doi.org/10.1016/j.egypro.2019.01.845.
69. Zhang, Z.; Dou, C.; Yue, D.; Zhang, B.; Zhao, P. High-economic PV power compensation algorithm to mitigate voltage rise with minimal curtailment. *Int. J. Electr. Power Energy Syst.* **2021**, *125*, 106401. https://doi.org/10.1016/j.ijepes.2020.106401.
70. Frew, B.; Sergi, B.; Denholm, P.; Cole, W.; Gates, N.; Levie, D.; Margolis, R. The curtailment paradox in the transition to high solar power systems. *Joule* **2021**, *5*, 1143–1167. https://doi.org/10.1016/j.joule.2021.03.021.

71. Borray, A.F.C.; Merino, J.; Torres, E.; Garcés, A.; Mazón, J. Centralised coordination of EVs charging and PV active power curtailment over multiple aggregators in low voltage networks. *Sustain. Energy Grids Netw.* **2021**, *27*, 100470. https://doi.org/10.1016/j.segan.2021.100470.
72. Gou, X.; Chen, Q.; Hu, K.; Ma, H.; Chen, L.; Wang, X.H.; Qi, J.; Xu, F.; Min, Y. Optimal planning of capacities and distribution of electric heater and heat storage for reduction of wind power curtailment in power systems. *Energy* **2018**, *160*, 763–773. https://doi.org/10.1016/j.energy.2018.07.027.
73. Nycander, E.; Söder, L.; Olauson, J.; Eriksson, R. Curtailment analysis for the Nordic power system considering transmission capacity, inertia limits and generation flexibility. *Renew. Energy* **2020**, *152*, 942–960. https://doi.org/10.1016/j.renene.2020.01.059.
74. Rochlin, C. Distributed renewable resources and the utility business model. *Electr. J.* **2016**, *29*, 7–12. https://doi.org/10.1016/j.tej.2015.12.001.
75. Dismukes, D.E.; Deupree, M.W. The challenges of the regulatory review of diversification mergers. *Electr. J.* **2016**, *29*, 8–14. https://doi.org/10.1016/j.tej.2016.04.009.
76. Satchwell, A.; Mills, A.; Barbose, G. Regulatory and ratemaking approaches to mitigate financial impacts of net-metered PV on utilities and ratepayers. *Energy Policy* **2015**, *85*, 115–125. https://doi.org/10.1016/j.enpol.2015.05.019.
77. Mihaylov, M.; Rădulescu, R.; Razo-Zapata, I.; Jurado, S.; Arco, L.; Avellana, N.; Nowé, A. Comparing stakeholder incentives across state-of-the-art renewable support mechanisms. *Renew. Energy* **2019**, *131*, 689–699. https://doi.org/10.1016/j.renene.2018.07.069.
78. Hoicka, C.E.; Lowitzsch, J.; Brisbois, M.C.; Kumar, A.; Ramirez Camargo, L. Implementing a just renewable energy transition: Policy advice for transposing the new European rules for renewable energy communities. *Energy Policy* **2021**, *156*, 112435. https://doi.org/10.1016/j.enpol.2021.112435.
79. Muqeet, H.A.; Munir, H.M.; Javed, H.; Shahzad, M.; Jamil, M.; Guerrero, J.M. An energy management system of campus microgrids: State-of-the-art and future challenges. *Energies* **2021**, *14*, 6525. https://doi.org/10.3390/en14206525.
80. Strunz, S.; Lehmann, P.; Gawel, E. Analyzing the ambitions of renewable energy policy in the EU and its Member States. *Energy Policy* **2021**, *156*, 112447. https://doi.org/10.1016/j.enpol.2021.112447.
81. Yunusov, T.; Torriti, J. Distributional effects of Time of Use tariffs based on electricity demand and time use. *Energy Policy* **2021**, *156*, 112412. https://doi.org/10.1016/j.enpol.2021.112412.
82. *UL Standard 1741*; Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources. UL: Bensenville, IL, USA, 2021.
83. *IEEE Standard 519*; Recommended Practice and Requirements for Harmonic Control in Electric Power Systems. IEEE: Piscataway, NJ, USA, 2014. https://doi.org/10.1109/IEEESTD.2014.6826459.
84. *IEC Standard 61727*; Photovoltaic (PV) Systems—Characteristics of the Utility Interface. IEC: Geneva, Switzerland, 2004.
85. *EN Standard 50160*; Voltage Characteristics of Electricity Supplied by Public Electricity Networks. EN: Brussels, Belgium, 2010.
86. Norouzi, F.; Hoppe, T.; Elizondo, L.R.; Bauer, P. A review of socio-technical barriers to Smart Microgrid development. *Renew. Sustain. Energy Rev.* **2022**, *167*, 112674. https://doi.org/10.1016/j.rser.2022.112674.
87. Cambini, C.; Meletiou, A.; Bompard, E.; Masera, M. Market and regulatory factors influencing smart-grid investment in Europe: Evidence from pilot projects and implications for reform. *Util. Policy* **2016**, *40*, 36–47. https://doi.org/10.1016/j.jup.2016.03.003.
88. Mohy-ud din, G.; Muttaqi, K.M.; Sutanto, D. Frequency Control Ancillary Services using Energy Storage in the Co-Optimized Energy Markets under Price Uncertainty. In Proceedings of the 2021 IEEE Industry Applications Society Annual Meeting (IAS), Virtual, 10–14 October 2021; pp. 1–6. https://doi.org/10.1109/IAS48185.2021.9677307.
89. Derks, M.; Romijn, H. Sustainable performance challenges of rural microgrids: Analysis of incentives and policy framework in Indonesia. *Energy Sustain. Dev.* **2019**, *53*, 57–70. https://doi.org/10.1016/j.esd.2019.08.003.
90. Benini, M.; Canevese, S.; Cirio, D.; Gatti, A. Battery energy storage systems for the provision of primary and secondary frequency regulation in Italy. In Proceedings of the 2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC), Florence, Italy, 7–10 June 2016; pp. 1–6. https://doi.org/10.1109/EEEIC.2016.7555748.
91. Liu, Y.; Bebic, J.; Kroposki, B.; Bedout, J.D.; Ren, W. Distribution system voltage performance analysis for high-penetration PV. In Proceedings of the 2008 IEEE Energy 2030 Conference, Atlanta, GA, USA, 17–18 November 2008. https://doi.org/10.1109/ENERGY.2008.4781069.
92. Spiliotis, K.; Gutierrez, A.I.R.; Belmans, R. Demand flexibility versus physical network expansions in distribution grids. *Appl. Energy* **2016**, *182*, 613–624. https://doi.org/10.1016/j.apenergy.2016.08.145.
93. Saygin, D.; Tör, O.B.; Cebeci, M.E.; Teimourzadeh, S.; Godron, P. Increasing Turkey's power system flexibility for grid integration of 50% renewable energy share. *Energy Strategy Rev.* **2021**, *34*, 100625. https://doi.org/10.1016/j.esr.2021.100625.
94. Iweh, C.D.; Gyamfi, S.; Tanyi, E.; Effah-Donyina, E. Distributed generation and renewable energy integration into the grid: Prerequisites, push factors, practical options, issues and merits. *Energies* **2021**, *14*, 5375. https://doi.org/10.3390/en14175375.
95. Goutte, S.; Vassilopoulos, P. The value of flexibility in power markets. *Energy Policy* **2019**, *125*, 347–357. https://doi.org/10.1016/j.enpol.2018.10.024.
96. Alizadeh, M.I.; Moghaddam, M.P.; Amjady, N.; Siano, P.; Sheikh-El-Eslami, M.K. Flexibility in future power systems with high renewable penetration: A review. *Renew. Sustain. Energy Rev.* **2016**, *57*, 1186–1193. https://doi.org/10.1016/j.rser.2015.12.200.
97. Bevrani, H.; Imanaka, M.; Kato, T. Grid dynamics shaping using flexible controlled power converters. *Energy Rep.* **2020**, *6*, 1490–1495. https://doi.org/10.1016/j.egyr.2020.10.065.

98. Collins, L.; Ward, J.K. Real and reactive power control of distributed PV inverters for overvoltage prevention and increased renewable generation hosting capacity. *Renew. Energy* **2015**, *81*, 464–471. https://doi.org/10.1016/j.renene.2015.03.012.
99. Mustafa, M.B.; Keatley, P.; Huang, Y.; Agbonaye, O.; Ademulegun, O.O.; Hewitt, N. Evaluation of a battery energy storage system in hospitals for arbitrage and ancillary services. *J. Energy Storage* **2021**, *43*, 103183. https://doi.org/10.1016/j.est.2021.103183.
100. Jankowiak, C.; Zacharopoulos, A.; Brandoni, C.; Keatley, P.; MacArtain, P.; Hewitt, N. Assessing the benefits of decentralised residential batteries for load peak shaving. *J. Energy Storage* **2020**, *32*, 101779. https://doi.org/10.1016/j.est.2020.101779.
101. Li, H.; Hou, J.; Tian, Z.; Hong, T.; Nord, N.; Rohde, D. Optimize heat prosumers' economic performance under current heating price models by using water tank thermal energy storage. *Energy* **2022**, *239*, 122103. https://doi.org/10.1016/j.energy.2021.122103.
102. Bahloul, M.; Khadem, S.K. Design and control of energy storage system for enhanced frequency response grid service. In Proceedings of the 2018 IEEE International Conference on Industrial Technology (ICIT), Lyon, France, 19–22 February 2018; pp. 1189–1194. https://doi.org/10.1109/ICIT.2018.8352347.
103. Sun, L.; Qiu, J.; Han, X.; Yin, X.; Dong, Z. Per-use-share rental strategy of distributed BESS in joint energy and frequency control ancillary services markets. *Appl. Energy* **2020**, *277*, 115589. https://doi.org/10.1016/j.apenergy.2020.115589.
104. Qingyuan, Y.; Aoki, M. Suppression of Voltage Fluctuation by Utilizing Consumer-Side Energy Storage Devices in PV Connected Distribution System. *IFAC-Pap.* **2018**, *51*, 432–437. https://doi.org/10.1016/j.ifacol.2018.11.741.
105. Abujubbeh, M.; Fahrioglu, M.; Al-Turjman, F. Power loss reduction and voltage enhancement via distributed photovoltaic generation: Case study in North Cyprus. *Comput. Electr. Eng.* **2021**, *95*, 107432. https://doi.org/10.1016/j.compeleceng.2021.107432.
106. Fonteijn, R.; Nguyen, P.H.; Morren, J.; Slootweg, J.G. Demonstrating a generic four-step approach for applying flexibility for congestion management in daily operation. *Sustain. Energy, Grids Netw.* **2020**, *23*, 100378. https://doi.org/10.1016/j.segan.2020.100378.
107. Barreto, R.; Faria, P.; Silva, C.; Vale, Z. Clustering direct load control appliances in the context of demand response programs in energy communities. *IFAC-Pap.* **2020**, *53*, 12608–12613. https://doi.org/10.1016/j.ifacol.2020.12.1827.
108. Duman, A.C.; Erden, H.S.; Ömer Gönül.; Önder Güler. A home energy management system with an integrated smart thermostat for demand response in smart grids. *Sustain. Cities Soc.* **2021**, *65*, 102639. https://doi.org/10.1016/j.scs.2020.102639.
109. Meng, Q.; Ren, X.; Wang, W.; Xiong, C.; Li, Y.; Xi, Y.; Yang, L. Reduction in on-off operations of an air source heat pump with active thermal storage and demand response: An experimental case study. *J. Energy Storage* **2021**, *36*, 102401. https://doi.org/10.1016/j.est.2021.102401.
110. AlFaris, F.; Juaidi, A.; Manzano-Agugliaro, F. Intelligent homes' technologies to optimize the energy performance for the net zero energy home. *Energy Build.* **2017**, *153*, 262–274. https://doi.org/10.1016/j.enbuild.2017.07.089.
111. Layate, Z.; Bahi, T.; Abadlia, I.; Bouzeria, H.; Lekhchine, S. Reactive power compensation control for three phase grid-connected photovoltaic generator. *Int. J. Hydrog. Energy* **2015**, *40*, 12619–12626. https://doi.org/10.1016/j.ijhydene.2015.07.087.
112. Bayer, B.; Marian, A. Innovative measures for integrating renewable energy in the German medium-voltage grids. *Energy Rep.* **2020**, *6*, 336–342. https://doi.org/10.1016/j.egyr.2019.12.028.
113. *IEEE Standard 1547-2018*; For Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces. IEEE: Piscataway, NJ, USA, 2018.
114. Sayeef, S.; Heslop, S.; Cornforth, D.; Moore, T.; Percy, S.; Ward, J.K.; Berry, A.; Rowe, D. *Solar Intermittency: Australia's Clean Energy Challenge Characterising the Effect of High Penetration Solar Intermittency on Australian Electricity Networks*; Available online: https://www.globalccsinstitute.com/archive/hub/publications/143773/solar-intermittency-australias-clean-energy-challenge.pdf (accessed on 28 December 2022).
115. Braithwait, S.D. Retail pricing responses to the challenge of distributed energy resources. *Electr. J.* **2018**, *31*, 38–43. https://doi.org/10.1016/j.tej.2018.09.001.
116. Pusceddu, E.; Zakeri, B.; Gissey, G.C. Synergies between energy arbitrage and fast frequency response for battery energy storage systems. *Appl. Energy* **2021**, *283*, 116274. https://doi.org/10.1016/j.apenergy.2020.116274.
117. Rana, M.M.; Romlie, M.F.; Abdullah, M.F.; Uddin, M.; Sarkar, M.R. A novel peak load shaving algorithm for isolated microgrid using hybrid PV-BESS system. *Energy* **2021**, *234*, 121157. https://doi.org/10.1016/j.energy.2021.121157.
118. Ceran, B.; Jurasz, J.; Mielcarek, A.; Campana, P.E. PV systems integrated with commercial buildings for local and national peak load shaving in Poland. *J. Clean. Prod.* **2021**, *322*, 129076. https://doi.org/10.1016/j.jclepro.2021.129076.
119. Kumar, D.S.; Gandhi, O.; Rodríguez-Gallegos, C.D.; Srinivasan, D. Review of power system impacts at high PV penetration Part II: Potential solutions and the way forward. *Solar Energy* **2020**, *210*, 202–221. https://doi.org/10.1016/j.solener.2020.08.047.
120. Fernández-Muñoz, D.; Pérez-Díaz, J.I.; Guisández, I.; Chazarra, M.; Álvaro Fernández-Espina. Fast frequency control ancillary services: An international review. *Renew. Sustain. Energy Rev.* **2020**, *120*, 109662. https://doi.org/10.1016/j.rser.2019.109662.
121. Tamrakar, U.; Shrestha, D.; Maharjan, M.; Bhattarai, B.P.; Hansen, T.M.; Tonkoski, R. Virtual inertia: Current trends and future directions. *Appl. Sci.* **2017**, *7*, 654. https://doi.org/10.3390/app7070654.
122. Rathbun, M.; Xu, Y.; Roofegari, R.; Qu, Z.; Sun, W. Impact Studies and Cooperative Voltage Control for High PV Penetration. *IFAC Pap.* **2018**, *51*, 684–689.
123. *ANSI Standard C841*; American National Standard for Electric Power Systems and Equipment—Voltage Ratings (60 Hz). ANSI: Washington, DC, USA, 2020.
124. Chaudhary, P.; Rizwan, M. Voltage regulation mitigation techniques in distribution system with high PV penetration: A review. *Renew. Sustain. Energy Rev.* **2018**, *82*, 3279–3287. https://doi.org/10.1016/j.rser.2017.10.017.

125. Hemmati, R.; Saboori, H.; Jirdehi, M.A. Stochastic planning and scheduling of energy storage systems for congestion management in electric power systems including renewable energy resources. *Energy* **2017**, *133*, 380–387. https://doi.org/10.1016/j.energy.2017.05.167.
126. Alotaibi, I.; Abido, M.A.; Khalid, M.; Savkin, A.V. A comprehensive review of recent advances in smart grids: A sustainable future with renewable energy resources. *Energies* **2020**, *13*, 6269. https://doi.org/10.3390/en13236269.
127. Xu, H.; Cheng, L.; Qi, N.; Zhou, X. Peak shaving potential analysis of distributed load virtual power plants. *Energy Rep.* **2020**, *6*, 515–525. https://doi.org/10.1016/j.egyr.2020.11.204.
128. Qi, N.; Cheng, L.; Xu, H.; Wang, Z.; Zhou, X. Practical demand response potential evaluation of air-conditioning loads for aggregated customers. *Energy Rep.* **2020**, *6*, 71–81. https://doi.org/10.1016/j.egyr.2020.12.019.
129. Rezaei, N.; Kalantar, M. Smart microgrid hierarchical frequency control ancillary service provision based on virtual inertia concept: An integrated demand response and droop controlled distributed generation framework. *Energy Convers. Manag.* **2015**, *92*, 287–301. https://doi.org/10.1016/j.enconman.2014.12.049.
130. Yilmaz, S.; Cuony, P.; Chanez, C. Prioritize your heat pump or electric vehicle? Analysing design preferences for Direct Load Control programmes in Swiss households. *Energy Res. Soc. Sci.* **2021**, *82*, 102319. https://doi.org/10.1016/j.erss.2021.102319.
131. Tang, R.; Wang, S.; Yan, C. A direct load control strategy of centralized air-conditioning systems for building fast demand response to urgent requests of smart grids. *Autom. Constr.* **2018**, *87*, 74–83. https://doi.org/10.1016/j.autcon.2017.12.012.
132. Oprea, S.V.; Bâra, A. Edge and fog computing using IoT for direct load optimization and control with flexibility services for citizen energy communities. *Knowl.-Based Syst.* **2021**, *228*, 107293. https://doi.org/10.1016/j.knosys.2021.107293.
133. Markensteijn, A.S.; Romate, J.E.; Vuik, C. A graph-based model framework for steady-state load flow problems of general multicarrier energy systems. *Appl. Energy* **2020**, *280*, 115286. https://doi.org/10.1016/j.apenergy.2020.115286.
134. Strehle, F.; Pfeifer, M.; Kölsch, L.; Degünther, C.; Ruf, J.; Andresen, L.; Hohmann, S. toward Port-Hamiltonian Modeling of MultiCarrier Energy Systems: A Case Study for a Coupled Electricity and Gas Distribution System. *IFAC-Pap.* **2018**, *51*, 463–468. https://doi.org/10.1016/j.ifacol.2018.03.078.
135. Khorsand, H.; Seifi, A.R. Probabilistic energy flow for multicarrier energy systems. *Renew. Sustain. Energy Rev.* **2018**, *94*, 989–997. https://doi.org/10.1016/j.rser.2018.07.008.
136. Kazemdehdashti, A.; Mohammadi, M.; Seifi, A.R.; Rastegar, M. Stochastic energy management in multicarrier residential energy systems. *Energy* **2020**, *202*, 117790. https://doi.org/10.1016/j.energy.2020.117790.
137. Rahmani, S.; Amjady, N. Optimal operation strategy for multicarrier energy systems including various energy converters by multiobjective information gap decision theory and enhanced directed search domain method. *Energy Convers. Manag.* **2019**, *198*, 111804. https://doi.org/10.1016/j.enconman.2019.111804.
138. Michaelides, E.E. Thermodynamics, energy dissipation, and figures of merit of energy storage systems—A critical review. *Energies* **2021**, *14*, 6121. https://doi.org/10.3390/en14196121.
139. Othman, A.M.; Gabbar, H.A. *Energy Storage Integration within Interconnected Micro Energy Grids*; Elsevier Inc.: Amsterdam, The Netherlands, 2017; pp. 207–220. https://doi.org/10.1016/B978-0-12-805343-0.00009-7.
140. Rohit, A.K.; Devi, K.P.; Rangnekar, S. An overview of energy storage and its importance in Indian renewable energy sector: Part I – Technologies and Comparison. *J. Energy Storage* **2017**, *13*, 10–23. https://doi.org/10.1016/j.est.2017.06.005.
141. Kuravi, S.; Trahan, J.; Goswami, D.Y.; Rahman, M.M.; Stefanakos, E.K. Thermal energy storage technologies and systems for concentrating solar power plants. *Prog. Energy Combust. Sci.* **2013**, *39*, 285–319. https://doi.org/10.1016/j.pecs.2013.02.001.
142. Mahon, H.; O'Connor, D.; Friedrich, D.; Hughes, B. A review of thermal energy storage technologies for seasonal loops. *Energy* **2022**, *239*, 122207. https://doi.org/10.1016/j.energy.2021.122207.
143. McKenna, P.; Turner, W.J.; Finn, D.P. Thermal energy storage using phase change material: Analysis of partial tank charging and discharging on system performance in a building cooling application. *Appl. Therm. Eng.* **2021**, *198*, 117437. https://doi.org/10.1016/j.applthermaleng.2021.117437.
144. Fernandes, D.; Pitié, F.; Cáceres, G.; Baeyens, J. Thermal energy storage: "How previous findings determine current research priorities". *Energy* **2012**, *39*, 246–257. https://doi.org/10.1016/j.energy.2012.01.024.
145. Mongird, K.; Viswanathan, V.V.; Balducci, P.J.; Alam, M.J.E.; Fotedar, V.; Koritarov, V.S.; Hadjerioua, B. *Energy Storage Technology and Cost Characterization Report*; Available online: https://energystorage.pnnl.gov/pdf/PNNL-28866.pdf (accessed on 28 December 2022).
146. Hannan, M.A.; Wali, S.B.; Ker, P.J.; Rahman, M.S.; Mansor, M.; Ramachandaramurthy, V.K.; Muttaqi, K.M.; Mahlia, T.M.; Dong, Z.Y. Battery energy-storage system: A review of technologies, optimization objectives, constraints, approaches, and outstanding issues. *J. Energy Storage* **2021**, *42*, 103023. https://doi.org/10.1016/j.est.2021.103023.
147. Yang, Y.; Okonkwo, E.G.; Huang, G.; Xu, S.; Sun, W.; He, Y. On the sustainability of lithium ion battery industry—A review and perspective. *Energy Storage Mater.* **2021**, *36*, 186–212. https://doi.org/10.1016/j.ensm.2020.12.019.
148. Lourenssen, K.; Williams, J.; Ahmadpour, F.; Clemmer, R.; Tasnim, S. Vanadium redox flow batteries: A comprehensive review. *J. Energy Storage* **2019**, *25*, 100844. https://doi.org/10.1016/j.est.2019.100844.
149. Emmett, R.K.; Roberts, M.E. Recent developments in alternative aqueous redox flow batteries for grid-scale energy storage. *J. Power Sources* **2021**, *506*, 230087. https://doi.org/10.1016/j.jpowsour.2021.230087.
150. Alqarni, M. Sodium sulfur batteries allocation in high renewable penetration microgrids using coronavirus herd immunity optimization. *Ain Shams Eng. J.* **2022**, *13*, 101590. https://doi.org/10.1016/j.asej.2021.09.017.

151. Li, Y.; Shi, L.; Gao, X.; Wang, J.; Hu, Y.; Wu, X.; Wen, Z. Constructing a charged-state Na-NiCl2 battery with NiCl2/graphene aerogel composite as cathode. *Chem. Eng. J.* **2021**, *421*, 127853. https://doi.org/10.1016/j.cej.2020.127853.
152. Quintero-Pulido, D.F.; Hoogsteen, G.; Kortenaar, M.V.T.; Hurink, J.L.; Hebner, R.E.; Smit, G.J. Characterization of storage sizing for an off-grid house in the US and the Netherlands. *Energies* **2018**, *11*, 265. https://doi.org/10.3390/en11020265.
153. Sankaralingam, R.K.; Seshadri, S.; Sunarso, J.; Bhatt, A.I.; Kapoor, A. Overview of the factors affecting the performance of vanadium redox flow batteries. *J. Energy Storage* **2021**, *41*, 102857. https://doi.org/10.1016/j.est.2021.102857.
154. Briot, L.; Petit, M.; Cacciuttolo, Q.; Pera, M.C. Aging phenomena and their modelling in aqueous organic redox flow batteries: A review. *J. Power Sources* **2022**, *536*, 231427. https://doi.org/10.1016/j.jpowsour.2022.231427.
155. Kumar, D.; Rajouria, S.K.; Kuhar, S.B.; Kanchan, D. Progress and prospects of sodium-sulfur batteries: A review. *Solid State Ionics* **2017**, *312*, 8–16. https://doi.org/10.1016/j.ssi.2017.10.004.
156. Kumar, D.; Kuhar, S.B.; Kanchan, D. Room temperature sodium-sulfur batteries as emerging energy source. *J. Energy Storage* **2018**, *18*, 133–148. https://doi.org/10.1016/j.est.2018.04.021.
157. Chemali, E.; Preindl, M.; Malysz, P.; Emadi, A. Electrochemical and Electrostatic Energy Storage and Management Systems for Electric Drive Vehicles: State-of-the-Art Review and Future Trends. *IEEE J. Emerg. Sel. Top. Power Electron.* **2016**, *4*, 1117–1134. https://doi.org/10.1109/JESTPE.2016.2566583.
158. Krishna, C.M. Managing battery and supercapacitor resources for real-time sporadic workloads. *IEEE Embed. Syst. Lett.* **2011**, *3*, 32–36. https://doi.org/10.1109/LES.2010.2098847.
159. Abdul Wahab, Y.; Naseer, M.N.; Zaidi, A.A.; Umair, T.; Khan, H.; Siddiqi, M.M.; Javed, M.S. Super Capacitors in Various Dimensionalities: Applications and Recent Advancements. In *Encyclopedia of Energy Storage*; Cabeza, L.F., Ed.; Elsevier: Oxford, UK, 2022; pp. 682–691. https://doi.org/10.1016/B978-0-12-819723-3.00020-2.
160. Behi, H.; Behi, M.; Ghanbarpour, A.; Karimi, D.; Azad, A.; Ghanbarpour, M.; Behnia, M. Enhancement of the thermal energy storage using heat-pipe-assisted phase change material. *Energies* **2021**, *14*, 6176. https://doi.org/10.3390/en14196176.
161. Mor, G.; Cipriano, J.; Grillone, B.; Amblard, F.; Menon, R.P.; Page, J.; Brennenstuhl, M.; Pietruschka, D.; Baumer, R.; Eicker, U. Operation and energy flexibility evaluation of direct load controlled buildings equipped with heat pumps. *Energy Build.* **2021**, *253*, 111484. https://doi.org/10.1016/j.enbuild.2021.111484.
162. Dai, Y.; Chen, L.; Min, Y.; Mancarella, P.; Chen, Q.; Hao, J.; Hu, K.; Xu, F. A General Model for Thermal Energy Storage in Combined Heat and Power Dispatch Considering Heat Transfer Constraints. *IEEE Trans. Sustain. Energy* **2018**, *9*, 1518–1528. https://doi.org/10.1109/TSTE.2018.2793360.
163. Fan, L.; Tu, Z.; Chan, S.H. Recent development of hydrogen and fuel cell technologies: A review. *Energy Rep.* **2021**, *7*, 8421–8446. https://doi.org/10.1016/j.egyr.2021.08.003.
164. Ishaq, H.; Dincer, I.; Naterer, G.F. Performance investigation of an integrated wind energy system for co-generation of power and hydrogen. *Int. J. Hydrog. Energy* **2018**, *43*, 9153–9164. https://doi.org/10.1016/j.ijhydene.2018.03.139.
165. İnci, M. Future vision of hydrogen fuel cells: A statistical review and research on applications, socio-economic impacts and forecasting prospects. *Sustain. Energy Technol. Assess.* **2022**, *53*, 102739. https://doi.org/10.1016/j.seta.2022.102739.
166. Yilanci, A.; Dincer, I.; Ozturk, H. A review on solar-hydrogen/fuel cell hybrid energy systems for stationary applications. *Prog. Energy Combust. Sci.* **2009**, *35*, 231–244. https://doi.org/10.1016/j.pecs.2008.07.004.
167. Kim, D.K.; Rho, K.H.; Na, Y.; Kim, M. Evaluation of energy storage technologies for efficient usage of wind power in the far-eastern region: A techno-economic analysis. *J. Energy Storage* **2021**, *39*, 102595. https://doi.org/10.1016/j.est.2021.102595.
168. Kumar, K.; Alam, M.; Dutta, V. Energy management strategy for integration of fuel cell-electrolyzer technologies in microgrid. *Int. J. Hydrog. Energy* **2021**, *46*, 33738–33755. https://doi.org/10.1016/j.ijhydene.2021.07.203.
169. Zhang, L.; Xiang, J. The performance of a grid-tied microgrid with hydrogen storage and a hydrogen fuel cell stack. *Energy Convers. Manag.* **2014**, *87*, 421–427. https://doi.org/10.1016/j.enconman.2014.07.045.
170. Kinnon, M.M.; Razeghi, G.; Samuelsen, S. The role of fuel cells in port microgrids to support sustainable goods movement. *Renew. Sustain. Energy Rev.* **2021**, *147*, 111226. https://doi.org/10.1016/j.rser.2021.111226.
171. *SAE Standard J1772*; Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler. SAE: Warren, PA, USA, 2017.
172. *INTECO Standard N121:2020*; Infraestructura de Centros de Recarga para Vehículos Eléctricos (VE). Requisitos. INTECO: Bruck an der Mur, Austria, 2020.
173. *IEC Standard 61851-1*; Electric Vehicle Conductive Charging System—Part 1: General Requirements. IEC: Geneva, Switzerland, 2017.
174. Colmenar-Santos, A.; Muñoz-Gómez, A.M.; Rosales-Asensio, E.; África López-Rey. Electric vehicle charging strategy to support renewable energy sources in Europe 2050 low-carbon scenario. *Energy* **2019**, *183*, 61–74. https://doi.org/10.1016/j.energy.2019.06.118.
175. Zheng, C.; Li, W.; Liang, Q. An Energy Management Strategy of Hybrid Energy Storage Systems for Electric Vehicle Applications. *IEEE Trans. Sustain. Energy* **2018**, *9*, 1880–1888. https://doi.org/10.1109/TSTE.2018.2818259.
176. Gilanifar, M.; Parvania, M. Clustered multinode learning of electric vehicle charging flexibility. *Appl. Energy* **2021**, *282*, 116125. https://doi.org/10.1016/j.apenergy.2020.116125.
177. Zhao, Y.; Wang, Z.; Shen, Z.J.M.; Sun, F. Data-driven framework for large-scale prediction of charging energy in electric vehicles. *Appl. Energy* **2021**, *282*, 116175. https://doi.org/10.1016/j.apenergy.2020.116175.
178. Lee, J.W.; Haram, M.H.S.M.; Ramasamy, G.; Thiagarajah, S.P.; Ngu, E.E.; Lee, Y.H. Technical feasibility and economics of repurposed electric vehicles batteries for power peak shaving. *J. Energy Storage* **2021**, *40*, 102752. https://doi.org/10.1016/j.est.2021.102752.

179. Glavin, M.E.; Hurley, W.G. Optimisation of a photovoltaic battery ultracapacitor hybrid energy storage system. *Solar Energy* **2012**, *86*, 3009–3020. https://doi.org/10.1016/j.solener.2012.07.005.
180. Jung, H.; Wang, H.; Hu, T. Control design for robust tracking and smooth transition in power systems with battery/supercapacitor hybrid energy storage devices. *J. Power Sources* **2014**, *267*, 566–575. https://doi.org/10.1016/j.jpowsour.2014.05.061.
181. Cabrane, Z.; Ouassaid, M.; Maaroufi, M. Analysis and evaluation of battery-supercapacitor hybrid energy storage system for photovoltaic installation. *Int. J. Hydrog. Energy* **2016**, *41*, 20897–20907. https://doi.org/10.1016/j.ijhydene.2016.06.141.
182. Zhu, Y.; Wang, H.; Zhu, Z. Improved VSG control strategy based on the combined power generation system with hydrogen fuel cells and super capacitors. *Energy Rep.* **2021**, *7*, 6820–6832. https://doi.org/10.1016/j.egyr.2021.10.056.
183. Rezzak, D.; Boudjerda, N. Robust energy management strategy based on non-linear cascade control of fuel cells-super capacitors hybrid power system. *Int. J. Hydrog. Energy* **2020**, *45*, 23254–23274. https://doi.org/10.1016/j.ijhydene.2020.05.250.
184. Zhou, Y.; Obeid, H.; Laghrouche, S.; Hilairet, M.; Djerdir, A. A novel second-order sliding mode control of hybrid fuel cell/super capacitors power system considering the degradation of the fuel cell. *Energy Convers. Manag.* **2021**, *229*, 113766. https://doi.org/10.1016/j.enconman.2020.113766.
185. Kadri, A.; Marzougui, H.; Aouiti, A.; Bacha, F. Energy management and control strategy for a DFIG wind turbine/fuel cell hybrid system with super capacitor storage system. *Energy* **2020**, *192*, 116518. https://doi.org/10.1016/j.energy.2019.116518.
186. Jami, M.; Shafiee, Q.; Gholami, M.; Bevrani, H. Control of a super-capacitor energy storage system to mimic inertia and transient response improvement of a direct current micro-grid. *J. Energy Storage* **2020**, *32*, 101788. https://doi.org/10.1016/j.est.2020.101788.
187. Shams, M.H.; Niaz, H.; Na, J.; Anvari-Moghaddam, A.; Liu, J.J. Machine learning-based utilization of renewable power curtailments under uncertainty by planning of hydrogen systems and battery storages. *J. Energy Storage* **2021**, *41*, 103010. https://doi.org/10.1016/j.est.2021.103010.
188. Li, Q.; Li, R.; Pu, Y.; Li, S.; Sun, C.; Chen, W. Coordinated control of electric-hydrogen hybrid energy storage for multimicrogrid with fuel cell/ electrolyzer/ PV/ battery. *J. Energy Storage* **2021**, *42*, 103110. https://doi.org/10.1016/j.est.2021.103110.
189. Patnam, B.S.K.; Pindoriya, N.M. Demand response in consumer-Centric electricity market: Mathematical models and optimization problems. *Electr. Power Syst. Res.* **2021**, *193*, 106923. https://doi.org/10.1016/j.epsr.2020.106923.
190. Datta, U.; Kalam, A.; Shi, J. Smart control of BESS in PV integrated EV charging station for reducing transformer overloading and providing battery-to-grid service. *J. Energy Storage* **2020**, *28*, 101224. https://doi.org/10.1016/j.est.2020.101224.
191. Khooban, M.H.; Niknam, T.; Blaabjerg, F.; Davari, P.; Dragicevic, T. A robust adaptive load frequency control for micro-grids. *ISA Trans.* **2016**, *65*, 220–229. https://doi.org/10.1016/j.isatra.2016.07.002.
192. Mendes, P.R.; Isorna, L.V.; Bordons, C.; Normey-Rico, J.E. Energy management of an experimental microgrid coupled to a V2G system. *J. Power Sources* **2016**, *327*, 702–713. https://doi.org/10.1016/j.jpowsour.2016.07.076.
193. Sun, L.; Qiu, J.; Han, X.; Yin, X.; Dong, Z.Y. Capacity and energy sharing platform with hybrid energy storage system: An example of hospitality industry. *Appl. Energy* **2020**, *280*, 115897. https://doi.org/10.1016/j.apenergy.2020.115897.
194. Weitzel, T.; Schneider, M.; Glock, C.H.; Löber, F.; Rinderknecht, S. Operating a storage-augmented hybrid microgrid considering battery aging costs. *J. Clean. Prod.* **2018**, *188*, 638–654. https://doi.org/10.1016/j.jclepro.2018.03.296.
195. Zhang, Y.; Meng, F.; Wang, R.; Kazemtabrizi, B.; Shi, J. Uncertainty-resistant stochastic MPC approach for optimal operation of CHP microgrid. *Energy* **2019**, *179*, 1265–1278. https://doi.org/10.1016/j.energy.2019.04.151.
196. Pan, Z.; Wu, J.; Sun, H.; Abeysekera, M. Quantification of Operational Flexibility from a Heating Network. *Energy Procedia* **2018**, *145*, 516–521. https://doi.org/10.1016/j.egypro.2018.04.075.
197. Alahäivälä, A.; Corbishley, J.; Ekström, J.; Jokisalo, J.; Lehtonen, M. A control framework for the utilization of heating load flexibility in a day-ahead market. *Electr. Power Syst. Res.* **2017**, *145*, 44–54. https://doi.org/10.1016/j.epsr.2016.12.019.
198. Salpakari, J.; Mikkola, J.; Lund, P.D. Improved flexibility with large-scale variable renewable power in cities through optimal demand side management and power-to-heat conversion. *Energy Convers. Manag.* **2016**, *126*, 649–661. https://doi.org/10.1016/j.enconman.2016.08.041.
199. Arabkoohsar, A. Non-uniform temperature district heating system with decentralized heat pumps and standalone storage tanks. *Energy* **2019**, *170*, 931–941. https://doi.org/10.1016/j.energy.2018.12.209.
200. Pieper, H.; Ommen, T.; Elmegaard, B.; Markussen, W.B. Assessment of a combination of three heat sources for heat pumps to supply district heating. *Energy* **2019**, *176*, 156–170. https://doi.org/10.1016/j.energy.2019.03.165.
201. Li, P.; Nord, N.; Ertesvåg, I.S.; Ge, Z.; Yang, Z.; Yang, Y. Integrated multiscale simulation of combined heat and power based district heating system. *Energy Convers. Manag.* **2015**, *106*, 337–354. https://doi.org/10.1016/j.enconman.2015.08.077.
202. Mohandes, B.; Acharya, S.; Moursi, M.S.E.; Al-Sumaiti, A.S.; Doukas, H.; Sgouridis, S. Optimal Design of an Islanded Microgrid With Load Shifting Mechanism Between Electrical and Thermal Energy Storage Systems. *IEEE Trans. Power Syst.* **2020**, *35*, 2642–2657. https://doi.org/10.1109/TPWRS.2020.2969575.
203. Masrur, H.; Shafie-Khah, M.; Hossain, M.J.; Senjyu, T. MultiEnergy Microgrids Incorporating EV Integration: Optimal Design and Resilient Operation. *IEEE Trans. Smart Grid* **2022**, *13*, 3508–3518. https://doi.org/10.1109/TSG.2022.3168687.
204. Li, P.; Huang, Y.; Qi, W.; Gan, J. Capacity Co-Optimization of Thermal and Battery Energy Storage System in Multienergy Complementary System. In Proceedings of the 2019 IEEE Innovative Smart Grid Technologies—Asia (ISGT Asia), Chengdu, China, 21–24 May 2019; pp. 3815–3819. https://doi.org/10.1109/ISGT-Asia.2019.8881407.

205. Wang, H.; Good, N.; Mancarella, P. Modelling and valuing multienergy flexibility from community energy systems. In Proceedings of the 2017 Australasian Universities Power Engineering Conference (AUPEC), Melbourne, Australia, 19–22 November 2017; pp. 1–6. https://doi.org/10.1109/AUPEC.2017.8282399.
206. Bagheri-Sanjareh, M.; Nazari, M.H.; Ebadat-Parast, M.; Hosseinian, S.H. Cooperative utilization of electrical and thermal storage systems for uninterruptible supply of a greenhouse Microgrid. In Proceedings of the 2021 11th Smart Grid Conference (SGC), Tabriz, Iran, 7–9 December 2021; pp. 1–6. https://doi.org/10.1109/SGC54087.2021.9664060.
207. Trairat, P.; Banjerdpongchai, D. Optimal Dispatch of Cogeneration with Thermal and Battery Energy Storage for BEMS Subject to Load Demand Uncertainty. In Proceedings of the 2022 19th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), Prachuap Khiri Khan, Thailand, 24–27 May 2022; pp. 1–4. https://doi.org/10.1109/ECTI-CON54298.2022.9795588.
208. Ha, T.; ZHANG, Y.J.; HUANG, V.V.T..J. Energy hub modeling to minimize residential energy costs considering solar energy and BESS. *J. Mod. Power Syst. Clean Energy* **2017**, *5*, 389–399. https://doi.org/10.1007/s40565-017-0281-4.
209. Geraedts, M.; Alpízar-Castillo, J.; Ramírez-Elizondo, L.; Bauer, P. Optimal Sizing of a Community Level Thermal Energy Storage System. In Proceedings of the 2022 IEEE 21st Mediterranean Electrotechnical Conference (MELECON), Palermo, Italy, 14–16 June 2022; pp. 52–57. https://doi.org/10.1109/MELECON53508.2022.9842945.
210. Aljabery, A.A.M.; Mehrjerdi, H.; Mahdavi, S.; Hemmati, R. Multi carrier energy systems and energy hubs: Comprehensive review, survey and recommendations. *Int. J. Hydrog. Energy* **2021**, *46*, 23795–23814. https://doi.org/10.1016/j.ijhydene.2021.04.178.
211. Thai, C.; Brouwer, J. Challenges estimating distributed solar potential with utilization factors: California universities case study. *Appl. Energy* **2021**, *282*, 116209. https://doi.org/10.1016/j.apenergy.2020.116209.
212. Ameur, A.; Berrada, A.; Loudiyi, K.; Adomatis, R. *Performance and Energetic Modeling of Hybrid PV Systems Coupled with Battery Energy Storage*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 195–238. https://doi.org/10.1016/b978-0-12-821403-9.00008-1.
213. Argyrou, M.C.; Marouchos, C.C.; Kalogirou, S.A.; Christodoulides, P. Modeling a residential grid-connected PV system with battery–supercapacitor storage: Control design and stability analysis. *Energy Rep.* **2021**, *7*, 4988–5002. https://doi.org/10.1016/j.egyr.2021.08.001.
214. Alpízar-Castillo, J. Simplified Model to Approach the Theoretical Clear Sky Solar PV Generation Curve through a Gaussian Approximation. *Niger. J. Technol.* **2021**, *40*, 44–48. https://doi.org/10.4314/njt.v40i1.7.
215. Newman, S.; Shiozawa, K.; Follum, J.; Barrett, E.; Douville, T.; Hardy, T.; Solana, A. A comparison of PV resource modeling for sizing microgrid components. *Renew. Energy* **2020**, *162*, 831–843. https://doi.org/10.1016/j.renene.2020.08.074.
216. Chong, L.W.; Wong, Y.W.; Rajkumar, R.K.; Isa, D. Modelling and Simulation of Standalone PV Systems with Battery-supercapacitor Hybrid Energy Storage System for a Rural Household. *Energy Procedia* **2017**, *107*, 232–236. https://doi.org/10.1016/j.egypro.2016.12.135.
217. Vega-Garita, V.; Ramirez-Elizondo, L.; Mouli, G.R.C.; Bauer, P. Review of residential PV-storage architectures. In Proceedings of the 2016 IEEE International Energy Conference (ENERGYCON), Leuven, Belgium, 4–8 April 2016. https://doi.org/10.1109/ENERGYCON.2016.7514039.