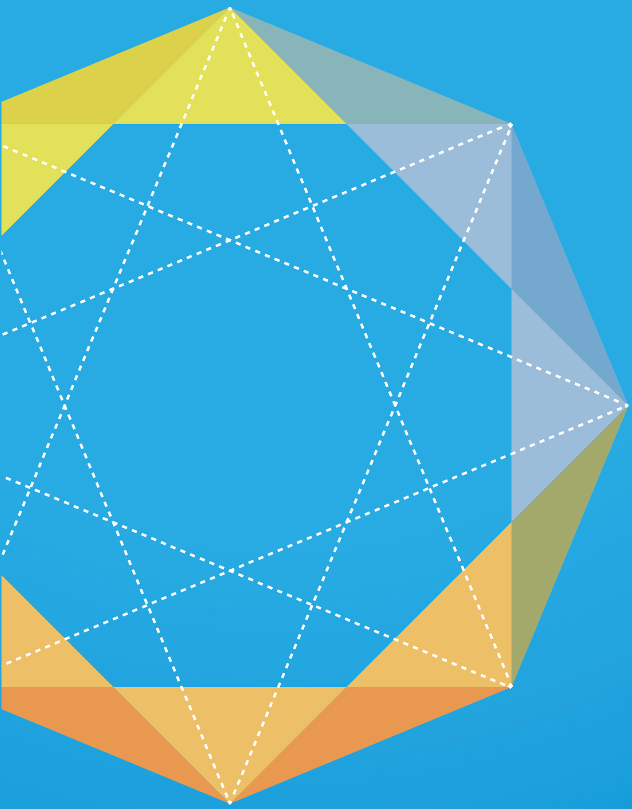
Ramp up of renewable generation flexibilities regarding to the system: focus on control solutions

ETIP SNET WG3



ETIP SNET

European Technology and Innovation Platform
Smart Networks for Energy Transition

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1 EXECUTIVE SUMMARY

Ramp up of renewable generation flexibilities regarding to the system: focus on control solutions

The increasing integration of renewable energy sources into global power systems presents unique challenges in terms of flexibility and control. Renewable energy sources such as wind and solar are inherently variable, making their management complex. This paper highlights the critical importance of control solutions, particularly digital ones, for ensuring the flexibility of renewable generation in future power systems.

Chapter 1 describes the European decarbonised context, where a high share of renewable sources is driving challenges in grid operation. It discusses the need for innovative control solutions to manage the variability of renewable energy sources, ensuring grid stability and reliability.

Chapter 2 focuses on the technical description of control solutions under a multilevel architecture. It delves into the design and implementation of digital control systems, including energy management systems (EMS) and power management systems (PMS), and asset control solutions like converter control to optimise the performance of renewable energy sources and their contribution to stabilise the power grid.

Chapter 3 offers an overview of EU projects on energy system control subjects. It highlights key initiatives and research efforts aimed at developing and deploying advanced control technologies to enhance the flexibility and efficiency of renewable energy.

Chapter 4 suggests research and innovation (R&I) recommendations for control solutions development, validation, and large-scale deployment. It identifies key areas for further research and development, including the integration of new control techniques such as artificial intelligence; digital twin and hardware-in-the-loop platforms, and cybersecurity mechanisms while also leveraging AI-driven forecasting for load, generation, and storage optimisation.

Key words: High rate RE system, flexibility, multi-level control, optimisation, interoperability, AI, EMS, inverter control

2 CONTEXT

2.1 Worldwide and European energy vision with high share of RE production

The EU aims to become a climate-neutral economy by 2050, which is now a legally binding target thanks to the European Climate Law1. The energy sector, responsible for more than 27% of greenhouse gas emissions in the EU2, is a central point of this transition and the electricity system is its backbone.

The European Commission expects that total electricity production will double by 2050, from the current 2,760 TWh to around 6,800 TWh, and that at least 80% of the total volume in 2050 will be provided by renewable energy sources. This shift is driven primarily by the expansion of variable renewable energy sources (VRES), i.e. solar and wind energy, which are expected to provide around 70% of the EU electricity mix3.

However, while those VRES are clean, at times abundant and increasingly cost-effective, their inherent variability introduces operational challenges that demand new approaches to system flexibility and control. A power system with a high share of VRES requires dynamic mechanisms to continuously balance the deviations between generation and demand, ensuring sufficient supply and grid stability. Thus, the success of the energy transition depends on the ability to integrate and manage these renewable energy sources effectively, leveraging advanced control solutions to enhance system flexibility.

2.2 Grid operation and key challenges

The large-scale integration of VRES affects the power system across different time spatial scales, requiring tailored solutions for effective system operation and planning.

In the short term, spanning milliseconds to seconds, grid stability is significantly challenged by the reduced system inertia resulting from the displacement of synchronous generators with renewable energy sources. This reduction weakens the system's ability to stabilise frequency deviations, necessitating the deployment of grid-forming inverters and fast-responsive energy storage systems to fill this gap. Additionally, the variability of RES introduces complications in primary control, disrupting real-time power balancing. Addressing these issues requires the development of advanced algorithms for automatic generation control (AGC) and the implementation of high-speed communication infrastructures to enhance monitoring and response accuracy. Without precise and rapid intervention mechanisms, the growing share of VRES could lead to increased frequency and voltage instability. Real-time control is thus a critical enabler of secure grid operations.

Over the medium term, from minutes to hours, reserve management becomes a central concern. Steep ramp-up or ramp-down events caused by fluctuating VRES output place strain on reserve resources like frequency containment reserve (FCR) and automatic frequency restoration reserve (aFRR). To manage these dynamics effectively, grid operators must leverage enhanced predictive analytics, incorporating machine learning and advanced weather and demand forecasting models to optimise reserve allocation. Beyond these supply-side solutions, demand-side flexibility plays a growing role: industrial load shifting and residential demand response can actively mitigate supply-demand imbalances, leveraging digital control systems to optimise consumption patterns.

In the long term, measured over hours to days, the challenge extends beyond operational balancing to system adequacy and resource planning. Prolonged periods of high VRES generation, such as those during favourable wind or solar conditions, may result in grid congestion or necessitate curtailment without sufficient reinforcements. Conversely, low VRES periods may create extended reliance on backup systems, emphasising the need for diverse energy storage technologies and their management. Here, control solutions play a crucial role in dynamically managing storage resources, coordinating flexible assets across different grid levels to ensure resilience in all scenarios.

Challenges also vary across spatial scales, with localised, regional, and national or transnational implications.

At the local distribution level, voltage stability issues are a common concern, particularly in areas with high penetration of distributed energy resources (DERs) such as rooftop solar PVs. Dynamic voltage regulation technologies and real-time monitoring systems are essential to address these challenges as well as control solutions which play a complementary and transformative role by enabling localised energy management, optimising DER operations, and ensuring system-wide coordination. For example, inverters with advanced control and grid-forming capabilities not only stabilise voltage but also dynamically adapt their output based on real-time

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[1] European Climate Law, https://climate.ec.europa.eu/eu-action/european-climate-law_en

[2] https://www.europarl.europa.eu/pdfs/news/ex -pert/2018/3/story/20180301STO98928/20180301STO98928_en.pdf

[3] Investing in a climate-neutral future for the benefit of our people, European Commission, https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020SC0176

grid conditions, enabling effective islanded operations and integration with the main grid.

At the regional interconnection level, the stochastic nature of wind and solar generation creates unpredictable power flows that increase the risk of bottlenecks within the grid. Flexible interconnection agreements and strategic grid upgrades are essential to mitigate these risks, but control solutions add an additional layer of efficiency by dynamically managing power flows and mitigating congestion in real time. For instance, adaptive control systems leveraging predictive analytics can anticipate congestion patterns and optimise grid usage. Furthermore, the displacement of conventional generators diminishes reactive power reserves, presenting challenges in ensuring power quality and managing loads effectively. Therefore, reactive power management must become a priority in regional grid operations.

On the national and transnational transmission level, cross-border coordination is a critical factor. Power exchanges driven by fluctuating VRES generation require harmonised market mechanisms and interconnectivity protocols. Control solutions are pivotal in facilitating these exchanges by ensuring grid stability across borders. For example, control platforms can synchronise the operation of multiple subsea transmission systems, dynamically balancing generation and load across interconnected regions. Alongside these physical considerations, the evolution of electricity markets is increasingly relevant. Day-Ahead (DA) and Intraday (ID) markets now play an indispensable role in balancing the grid under high-RES penetration. Control algorithms are essential for market participants to provide ancillary services, optimise asset bidding strategies, and respond to real-time price signals. These tools enable both transmission system operators (TSOs) and market operators to dynamically procure flexibility resources, while DSOs adopt new control responsibilities to support local markets effectively.

2.3 Future energy systems growing need for flexibility

To ensure a secure and resilient grid in a high-RES future, system flexibility must be significantly enhanced. According to ENTSO-E, “system flexibility” is defined as “the ability of the power system to cope with variability and uncertainty in demand, generation and grid availability”4. As the electrification of heating, transport and industry accelerates, Europe’s future energy system will become increasingly weather-dependent, since the electricity system will heavily depend on VRES.

Figure 1 illustrates the contributions of various renewable energy sources, focusing on VRES (solar and wind) to total demand and residual load over a period of a month, highlighting fluctuations and the need for flexibility. The concept of residual load is central to understanding the flexibility needs of a renewable-dominated energy system. With massive VRES integration, the residual load fluctuates significantly, driven by variations in the renewable production. Therefore, it clearly emerges how flexibility resources, including storage, demand response, and dispatchable renewables are essential to bridge the gap and ensure both reliable power supply and profitable assets management.

Flexibility is now recognised as one of the three key pillars of Europe’s future power system. It is needed to compensate for both short-term fluctuations and long-term variability, leading to the development of new flexibility solutions across different timeframes:

- Short- and medium duration flexibility (from milliseconds to a few hours) ensures intra-day stability and system security, relying on fast-response assets such as grid-forming inverters, demand-side response, and fast-acting storage systems:

- Long-duration flexibility (from days to several weeks) addresses prolonged shortages of VRES, necessitating large-scale and long-term storage solutions such as hydrogen (already exposed in an ETIP SNET publication[5]), hybrid AC-DC networks architecture and advanced energy storage integration.

To unlock these flexibilities, control systems must evolve, moving beyond conventional grid management to real-time optimisation of distributed assets, leveraging digitalisation and automation to maximise flexibility potential. Advanced control architectures are key enablers for coordinating diverse flexibility resources, optimising their development, and ensuring seamless system operation across grid levels.

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[4] https://vision.entsoe.eu/chapters/energy-system-flexibility

[5] Hydrogen’s impact on grids – Impact of hydrogen integration on power grids and energy systems, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2833/556144

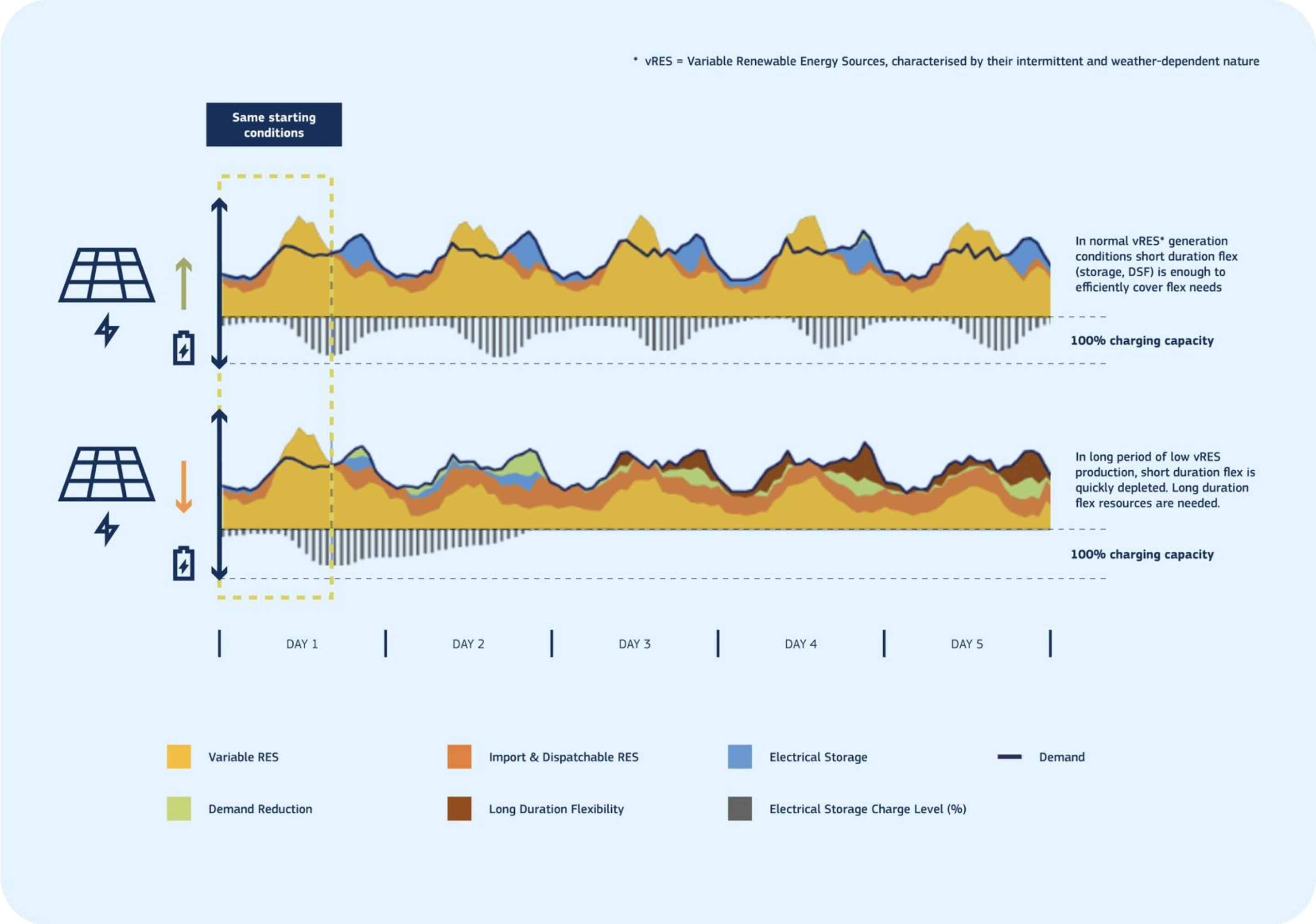

Figure 1 - Residual load (grey bars) variation according to renewable rate scenario: high rate (on top) and low rate (bottom) that represents flexibility needs [ENTSO-E]

So, apart from the distinction between its use in demand, generation or grid availability, flexibility solutions can be classified according to different criteria6 such as:

- Timescale: in line with grid operation various timescales, corresponding flexibility needs to be provided.
- Use case: large-scale (TSO level), i.e. most wind farms, around one third of PV generation in Europe; distributed renewable energy systems (DSO level); energy communities; commercial and industrial buildings and installations; residential buildings and EV. Control systems can be designed at each of these levels, with some common and some features for all of them.
- Level of digitalisation: from solutions that are primarily digital or at least strongly digitally enabled that build on existing infrastructure, to purpose-built non-digital flexibility solutions such as utility-scale batteries and gas power plants.
- Other aspects: flexibility impact, market segments, stakeholder mapping, innovation assessment, economic viability, technical assessment and risk.

ETIP-SNET High Level Use Cases (HLUC) and their corresponding Priority Project Concepts (PPCs) cover these different approaches[7]. While system control solutions span multiple control timescales, this paper focuses on scalable control strategies that enhance

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[6] European Commission: Directorate-General for Energy, Antretter, M., Klobasa, M., Kühnbach, M., Singh, M. et al., Digitalisation of energy flexibility, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2833/113770

[7] European Commission: Directorate-General for Energy, Souza e Silva, N., Strbac, G., Monti, A., Provaggi, A. et al., ETIP SNET, R&I implementation plan 2022-2025, Dimeas, A.(editor), Staschus, K.(editor), Bacher, R.(editor), Karakitsios, J.(editor) and Hatziargyriou, N.(editor), Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2833/361546

flexibility of large-scale (TSO level), and medium-scale (~MW sites) distributed renewable energy systems (DSO level), mainly at the generation level. This analysis considers control objectives such as the participation in various energy and power markets across grid levels, however excludes sub-second stability control, which is a specialised domain of power system stability.

3 TECHNICAL FOCUS

With ever higher shares of renewable generation, global energy systems are becoming highly decentralised. They are composed of numerous local energy systems which need a controller both to provide flexibility services to the overall network, and to ensure local operation requirement. For example, a hybrid PV (photovoltaic) storage system may provide ancillary services to a power system while optimising its self-consumption rate. Hierarchical control architecture has been adopted as one of the main approaches as illustrated in Figure 2 below. Depending on energy system configuration, power scale and connection, its control system might cover one or more layers among those mentioned.

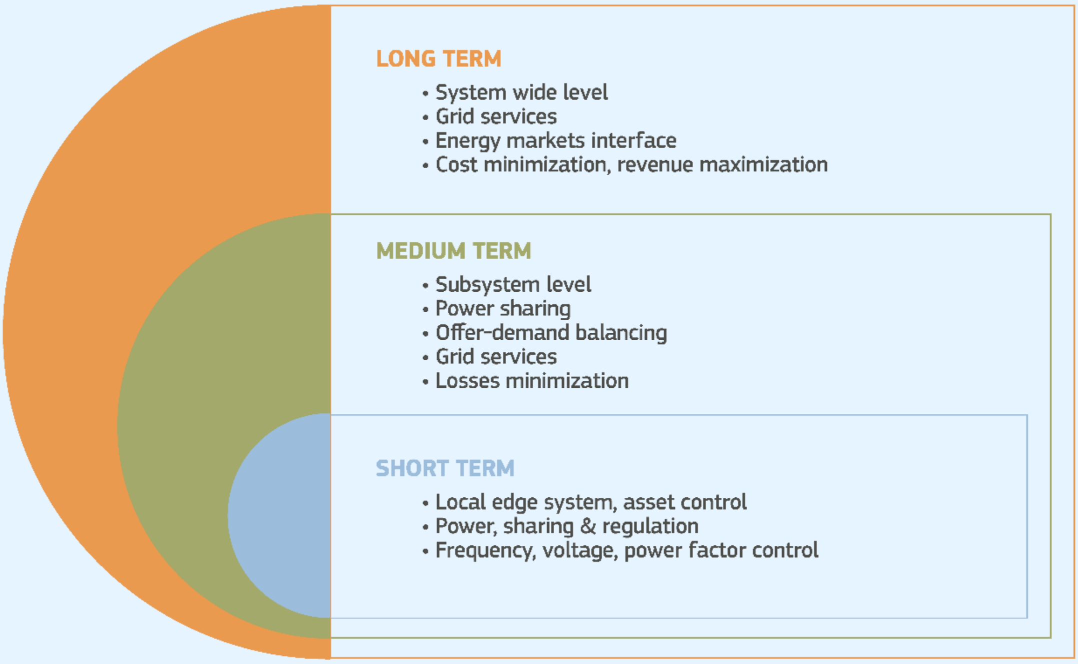

Figure 2 - Hierarchical control architecture

This multi-level control architecture has been designed to manage and optimise the operation of energy systems. It consists of three different control levels, differentiated by temporal and functional scales. At the short-term control level, control actions ensure rapid power sharing, in response to fluctuations in generation (e.g., in case of uncertain forecasting) as well as power adjustments to voltage / power factor regulation purposes. Usually, this control level is hosted by a programmable logic component (PLC) or an iPC (industrial control) made of algorithms integrated in the local edge system and device-level controllers (such as the case of inverters). Medium-term control operates at the local grid or subsystem level and focuses on managing interactions between various assets using real-time data acquisition and predictive analysis. The last control level operates at the system-wide level and focuses on long-term and strategic energy management by optimising economic outcomes over periods ranging from minutes to weeks, while ensuring that the system can contribute to broader grid services, including peak shaving and ancillary support. This control typically relies on cloud-based computing platforms. These multi-level control architectures are increasingly integrated into cloud-edge structures, which leverage centralised computing for long-term optimisation while ensuring localised, secure, and fast responses through edge-based control layers.

This division can be slightly different in various system designs. In some complex systems, there may be more than three control layers. In figure 3 below a utility-scale hybrid power plant[8] (HPP) using a hierarchical control architecture is presented, with four control

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[8] Qian Long, Kaushik Das, Daniel V. Pombo, Poul E. Sørensen. Hierarchical control architecture of co-located hybrid power plants, International Journal of Electrical Power & Energy Systems, Volume 143, 2022, 108407, ISSN 0142-0615,

levels, is presented. From top to bottom (from left to right in Figure 3), the four layers are: HPP energy management system (EMS) level for system-wide long-term management, HPP control level in charge of plant's global power exchange with the external grid, plant control level for each component power control and asset control level for component internal regulation. Higher control levels have a longer time resolution (minutes up to hours) and vice versa (asset control level acts in the range of milliseconds to seconds).

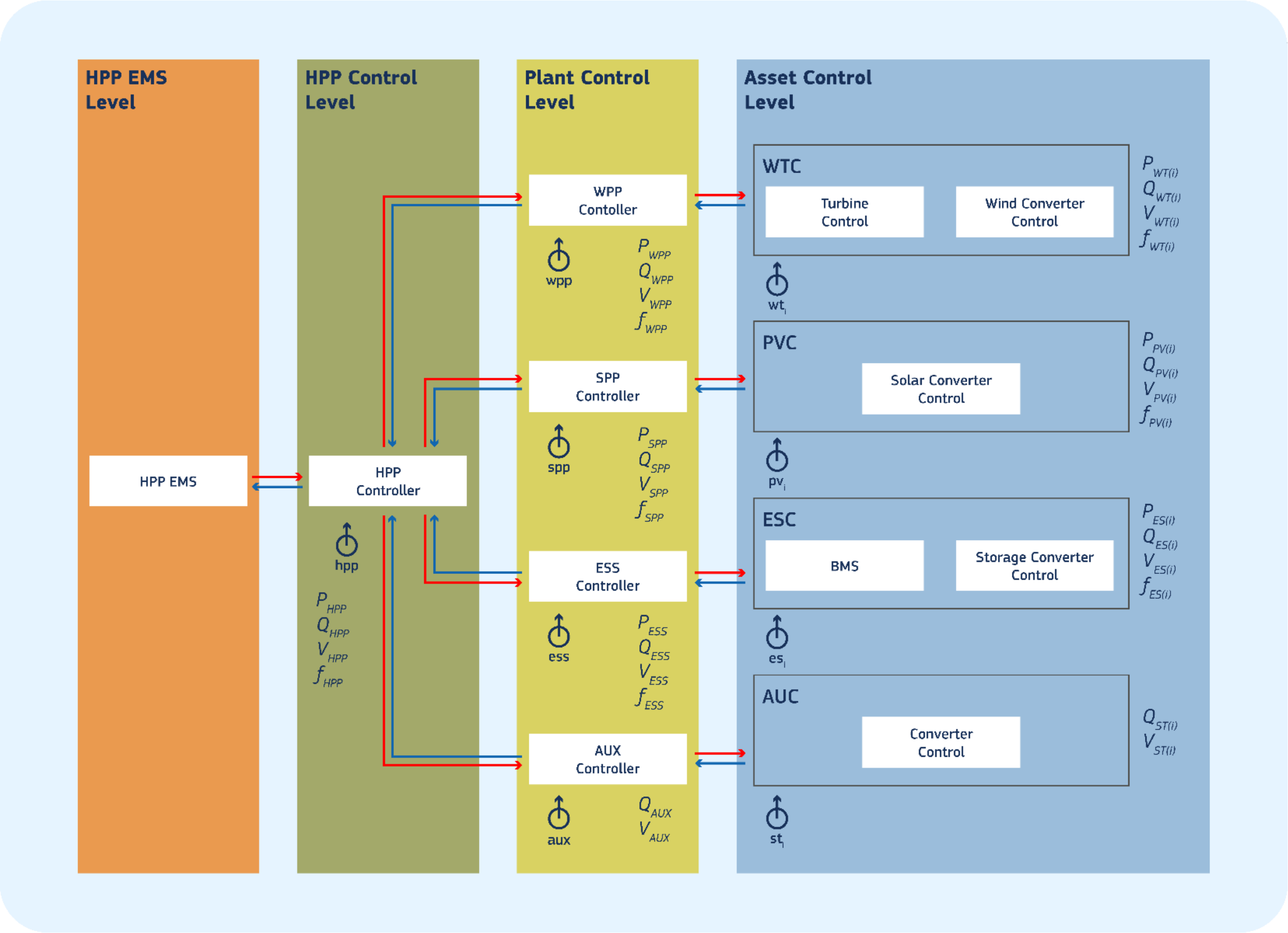

Figure 3 - Example of four-layer control in a utility-scale hybrid power plant composed of a WPP (wind power plant), an SPP (solar power plant), an ESS (energy storage system) and an AUX (auxiliary system)

In common terminologies, EMS term is used for control layers that are fulfilled by digital techniques. Thus, it commonly covers medium- and long-term control level actions. For real-time control actions, they can be a digital or physical controller, carried either by the PMS unit, in case of system centralised control, or by the asset controller itself. Related to the hierarchical architecture, these real-time controllers cover the short-term layer, and some functionalities are listed in the medium-term layer.

EMSs have often been investigated in the context of microgrids, where optimisation refers to supplying a certain load. In utility-scale power plants, this is not the case, as the power plant is assumed to be small compared to the overall power system. The idea is to address all the control layers in this publication, covering both EMS and PMS, and even some real-time control at the asset level (inverter control). In the remainder of this paper, the controls are discussed under two categories: digital control on system/plant (EMS and PMS) and the local asset control.

3.1 Digital control: key technical aspects to target flexibility optimisation

As renewable generation and power consumers become more integrated into the power system, EMS must evolve to accommodate local needs while offering flexibility to the broader grid. The complexity of the EMS optimisation problem increases due to the diverse range of assets, markets, and service-related objectives. Depending on the energy system's characteristics and goals, the functions of

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https://doi.org/10.1016/j.ijepes.2022.108407 an EMS may vary, including:

- Optimising energy revenues from multiple energy markets
- Contributing to grid services such as ancillary services, peak shaving, and peak supply
- Reducing local energy consumption costs
- Minimising energy losses

The construction of an efficient EMS requires the integration of a diverse range of methodologies, each offering distinct advantages depending on the complexity and objectives of the system. As the energy system evolves, new methods are required to construct EMSs that meet today's modern requirements and challenges, and contribute to enhanced efficiency, reduced costs, and increased integration of renewable energy sources.

Additional elements contribute much to enhancing EMS performance, including:

- Forecasting production (e.g., solar, wind) and consumption
- Robust communication infrastructure, such as smart metering, data spaces and cybersecurity
- Optimisation techniques, including the development and validation of models and solvers
- Software and experimental tools that support the development and validation of EMS solutions
- Capacity enhancing technologies like dynamic line rating (DLR) and dynamic asset rating (DAR) enable scalable solutions for grid flexibility management

Emerging concepts, such as cloud-edge structures, offer innovative solutions. These systems combine spatial-based coordination, enabling the coordination of multiple EMS units. The cloud-based layer, typically used for long-term optimisation, handles system-of-systems calculations, supporting the energy management of multi-sites or microgrids. This layer also facilitates remote access to crucial energy-related data and tools, removing geographical limitations. In contrast, the edge-based layer, located closer to the site, focuses on short-term, local actions and addresses cybersecurity concerns. This architecture improves scaleability, accommodating the evolving needs of the system and allowing for the addition of more assets or sites into the same EMS.

3.1.1 Main control techniques

Energy optimisation and flexibility management are usually the most diffuse functions of EMS solutions, the former aiming at minimising costs and losses while maximising renewable integration and system efficiency, the latter aiming at balancing the variability of renewable energy sources with demand, storage and grid requirements. Apart from these, EMS solutions are also devoted to enabling interactions with energy markets, here including ancillary service.

State-of-the-art EMS solutions incorporate advanced optimisation frameworks to enhance their performance, as well as to account for environmental, economic and operational goals[9] [10] [11]. In other cases, stochastic models are widely used to address uncertainties in renewable energy production, such as solar and wind, as well as in consumption forecasting[12] . At the same time, the rapid evolution of AI-based tools and environments has further improved the EMS capabilities. In this case, the main applications are devoted to the

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[9] F. Ceglia, P. Esposito, A. Faraudello, E. Marrasso, P. Rossi, M. Sasso, "An energy, environmental, management and economic analysis of energy efficient system towards renewable energy community: The case study of multi-purpose energy community", Journal of Cleaner Production, Volume 369, 1 October 2022, 133269, doi.org/10.1016/j.jclepro.2022.133269.

[10] F. Ceglia, E. Marrasso, C. Roselli, M. Sasso, "Time-evolution and forecasting of environmental and energy performance of electricity production system at national and at bidding zone level", Energy Conversion and Management, Volume 265, 1 August 2022, 115772, doi.org/10.1016/j.enconman.2022.115772

[11] B. Durillon, A. Bossu, „Environmental assessment of smart energy management systems at distribution level — A review", Renewable and Sustainable Energy Reviews, Volume 203, October 2024, 114739, doi.org/10.1016/j.rser.2024.114739

[12] M. Fayyazi, M. Abdoos, D. Phan, M. Golafrouz, M. Jalili, R. N. Jazar, R. Langari, H. Khayyam, "Real-time self-adaptive Q-learning controller for energy management of conventional autonomous vehicles", Expert Systems with Applications, Volume 222, 15 July 2023, 119770, doi.org/10.1016/j.eswa.2023.119770.

enhancement of dynamic forecasting, decision-making optimisation, anomaly detection, and self-adapting control[13].

Other possible EMS solutions refer to the adoption of ad hoc defined simulation environments and digital twin technologies, used to validate EMS performance prior to deployment and focusing on criteria such as scaleability, fault tolerance, and adaptability to evolving energy market demands[14].

In order to implement EMS solutions and ensure their efficient operation, several methodologies and techniques can be adopted. These methodologies can be classified as rule-based (RB) methodology, mathematical optimisation (MO), model predictive control (MPC), deep reinforcement learning (DRL), and stochastic dynamic programming (SDP). Each of the existing techniques presents certain advantages and challenges; hence, the choice of the most suitable method depends on the required characteristics for the EMS under development. While the industry mostly uses optimisation techniques for market participation, it maintains rule-based methods for internal dispatch due to their robustness even if this results in non-optimal operation. Some of these methodologies are described below.

Machine learning (ML)

In ML, decisions and predictions are based on a complex learning of statistical models and datasets. ML can be categorised into supervised learning (where learning is based on labelled datasets), unsupervised learning (which uses unlabelled datasets), reinforcement learning (learning through trial and error), and deep learning (which uses neural networks to model relationships). ML15 plays a significant role in the development of EMSs by ensuring smart decision-making and optimisation according to required objectives (cost reduction, energy efficiency, emissions reduction). In general, supervised learning is often used for data forecasting which helps in predicting renewable energy generation. On the other hand, unsupervised learning is usually used for identifying generation patterns of PV or wind systems, for example. Reinforcement-learning techniques, on the other hand, enable adaptive control strategies that contribute to the development of inverter power adjustment strategies and real-time dispatching. The integration of ML techniques in EMS implementation results in a robust and smart system capable of handling complex problems and dealing with system uncertainties, without the need to explicitly model the EMS structure.

Deep learning

Deep learning techniques16 use artificial neural networks in order to model and understand datasets. The name “neural networks” comes from their association with human neurons interconnections. These consist of multiple layers that process input data to extract features, enabling data classification, prediction and decision-making functions. Deep learning techniques are especially used in handling large data structures and hence represent a powerful tool in developing EMSs for complex and decentralised energy networks. Depending on the objectives considered, several types of neural networks exist; for example, recurrent neural networks (RNNs) for energy demand prediction, and convolutional neural networks (CNNs) for optimising DERs.

Despite their convenience, several challenges emerge with the use of AI techniques such as data related challenges since development of these models require precise, and available datasets that illustrate real-life study cases. In addition, development of AI techniques on a large-scale EMS requires large computation time and storage capacity. Although AI techniques are well developed in literature, real use of these techniques still seems challenging with the existing limited infrastructure and data availability.

Optimisation techniques

Optimisation techniques17 18 play an important role in EMS implementation by ensuring efficiency and reliability of the model while

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[13] T. C. Brito, M.A. Brito, “Forecasting of Energy Consumption: Artificial Intelligence Methods”, Conference: 2022 17th Iberian Conference on Information Systems and Technologies (CISTI), June 2022, DOI: 10.23919/CISTI54924.2022.9820078.

[14] Matteo Cossutta, Seksak Pholboon, Jon McKechnie, Mark Sumner, “Techno-economic and environmental analysis of community energy management for peak shaving”, Energy Conversion and Management, Volume 251, 1 January 2022, 114900, doi.org/10.1016/j.enconman.2021.114900.

[15] R. A. Iringan Iii, A. M. S. Janer, and L. A. R. Tria, “A Machine-learning Based Energy Management System for Microgrids with Distributed Energy Resources and Storage,” in 2022 25th International Conference on Electrical Machines and Systems (ICEMS), Nov. 2022, pp. 1–6. doi: 10.1109/ICEMS56177.2022.9983198

[16] P. Boopathy, “Deep learning for intelligent demand response and smart grids: A comprehensive survey,” *Comput. Sci. Rev.*, 2024

[17] Shufian and N. Mohammad, “Modeling and analysis of cost-effective energy management for integrated microgrids,” *Clean. Eng. Technol.*, vol. 8, p. 100508, Jun. 2022, doi: 10.1016/j.clet.2022.100508

[18] S. H. Mirbarati, N. Heidari, A. Nikoofard, M. S. S. Danish, and M. Khosravy, “Techno-Economic-Environmental Energy Management of a Micro-Grid: A Mixed-Integer Linear Programming Approach,” *Sustainability*, vol. 14, no. 22, Art. no. 22, Jan. 2022, doi: 10.3390/su142215036.

addressing key challenges such as load balancing and energy storage management.

Mathematical programming represents one of the most widely used optimisation approaches in EMSs. These techniques require system modelling; however, they offer exact approaches that are capable of generating precise and optimal solutions. Mathematical programming methods such as linear programming (LP) and non-linear programming (NLP) are usually used for minimising cost and optimising energy storage. Mixed-Integer programming (MIP) is mostly implemented when considering energy scheduling, while quadratic programming (QP) optimises problems with quadratic objectives such as power loss minimisation.

On the other hand, approximate approaches are capable of achieving near-optimal results and are most commonly used in complex problem-solving scenarios where short computation time is required and the solution space is vast. Approximate methods include heuristic and meta-heuristic approaches, like genetic algorithm (GA) and particle swarm optimisation (PSO), which are mostly effective for demand response and DER scheduling problems.

Other approximate methods include model predictive control (MPC)19, which improves system adaptability by allowing continuous adjustment of optimisation decisions according to real-time data. MPC has become one of the most used methods in the literature when it comes to EMS development because it allows modern EMSs to be capable of managing dynamic systems. In addition, stochastic optimisation techniques are becoming increasingly important due to the necessity of dealing with uncertainty in intermittent energy resources like solar and wind. These methods incorporate probabilistic models to address uncertainty in energy generation and demand forecasts, enabling robust decision-making under varying conditions.

Using these optimisation techniques, EMSs are able to integrate VRES in an efficient manner while ensuring optimality of solutions and adaptability of the developed model. However, the complexity of energy networks continues to increase, requiring decentralised and complex EMSs and hence further developed optimisation methods.

Hybrid techniques

Hybrid techniques[20] allow a combination of strengths present in certain methodologies, such as optimisation and machine learning. This ensures optimal solutions while integrating learning and prediction capacities into the EMS model, making the system adaptable and more robust. In a similar manner, GA and PSO can be combined with mathematical programming to enhance efficiency and optimality in non-linear or large-scale problems. Such hybrid techniques allow the EMS to handle uncertainty and improve the decision-making process, making the EMS structure more efficient and developed to address existing challenges.

Hybrid techniques can be used in different EMS structures; however, they are especially used in distributed or decentralised control structures such as multi-agent systems (MAS). MAS enables decentralised decision-making by allowing multiple autonomous agents to participate in optimisation. When combined with machine learning, MAS demonstrates high flexibility of the EMS model and adaptability by enabling agents to make local decisions according to global optimisation objectives, which creates a multi-level hybrid control strategy.

Comparative analysis

The overview of the strengths and weaknesses of some of these techniques is summarised in Table 1.

Table 1 - Strengths and weaknesses of EMS methodologies

Method	Strengths	Weaknesses
Rule-based	• Fast computation time • Simple to implement and understand	• Limited flexibility and adaptability • May not handle uncertainty well

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[19] F. Kamal and B. Chowdhury, “Model predictive control and optimisation of networked microgrids,” *Int. J. Electr. Power Energy Syst.*, vol. 138, p. 107804, Jun. 2022, doi: 10.1016/j.ijepes.2021.107804

[20] 14 W. Cai, A. B. Kordabad, and S. Gros, “Energy management in residential microgrid using model predictive control-based reinforcement learning and Shapley value,” *Eng. Appl. Artif. Intell.*, vol. 119, p. 105793, Mar. 2023, doi: 10.1016/j.engappai.2022.105793

Mathematical programming	• Guarantees performance in worst-case scenarios • Possible trade-off between optimality and computation time	• Dependent on the quality of the model and data • High computational demand
Approximate optimization (heuristic & meta-heuristic)	• Fast computation time	• No guarantee of global optimum
MPC (Model Predictive Control)	• Suitable for problems with continuous decision updates • Handles uncertainty	• High computational demand • Complex implementation
Stochastic	• Handles uncertainty	• High computational demand • Complex implementation
AI (Artificial Intelligence)	• Handles complex, high-dimensional problems	• Requires large amounts of data • Solution may not be feasible
Hybrid (mathematical & approximate)	• Greater adaptability and efficiency for non-linear and large-scale problems • Handles uncertainty	• Complex implementation
Hybrid (mathematical & machine learning)	• High flexibility and adaptability of the EMS model	• Complex implementation

3.1.2 Limitations on development, validation and deployment

EMS solutions have been thoroughly investigated by a large number of academic R&D and industrial companies whose business cases vary from system operators, energy vendors, equipment suppliers (inverters, storage), project designers, digital solutions provider (controller offers or services offers such as energy forecast, etc.). These solutions are often developed for specific use cases, with both economic and robustness challenges. Generic models and tools are needed to facilitate EMS development, validation, and scaling up.

The validation and deployment of EMS solutions face several limitations. One of the most significant challenges lies in data collection and their quality[21]. Accurate forecasting of energy production (and, in some cases, consumption) relies heavily on the availability of high-quality, high-resolution data. However, achieving this is challenging due to data unavailability or inconsistencies across different regions and systems. One approach to address this is to incorporate external data sources, such as simulations and predictions, although this may still constrain the optimal performance of the EMS. Concurrently, real-time, multi-level optimisation leads to a significant increase in computational complexity as system size grows.

Another limit consists of the standardisation gaps for EMS deployment. A lack of standardised protocols for communication and interoperability restricts the integration of EMS across different energy systems, with the addition of regional regulatory differences that hinder the deployment of widely standardised systems[22].

3.1.3 Regulatory/ business model/ market

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[21] Z. Allal, H. N. Noura, O. Salman, et K. Chahine, « Machine learning solutions for renewable energy systems: Applications, challenges, limitations, and future directions », Journal of Environmental Management, vol. 354, p. 120392, 2024, doi: https://doi.org/10.1016/j.jenvman.2024.120392.

[22] «Data-driven energy management of virtual power plants: A review», Advances in Applied Energy, vol. 14, p. 100170, juill. 2024, doi: 10.1016/j.adapen.2024.100170.

Advanced EMS solutions also encounter high initial costs, which are significant for developers and investors. Under this framework, cybersecurity also plays a significant role, as the need for an increasing connectivity introduces vulnerabilities that can dissuade people from adopting these solutions. The development and use of EMS solutions should be aligned with the limitations of regulatory frameworks and directives like those for cybersecurity, AI applications, data ownership, privacy regulations, etc. Finally, another point of discussion refers to the market adaptation, as most current EMS solutions are often tailored to specific uses cases, making them less flexible for evolving market conditions. Moreover, their integration into ancillary service markets of virtual power plants is still not fully developed[23].

To overcome these limitations, several recommendations can be implemented. First, the promotion of standardisation is critical, as well as the need to have a regulatory alignment encouraging innovation and reducing financial (through incentives) and operational costs (through compliance guidelines) for stakeholders. At the same time, the spread of validation platforms, robust digital twins and hybrid physical-digital simulation environments can be fostered in order to improve reliability and adaptability of EMS. Table 2 summarises some industrial EMS tools and their applications in real-world HPPs. However, all the EMS tools for HPPs are proprietary in the industry.

Table 2 - Overview of industrial EMS tools and real-world applications[24]

Tool	Developer	Application and Location
FLEXIQ Dispatcher	General Electric	Lenox Solar / Energy Storage, USA
GEMS IntelliBidder	Wärtsilä	Hickory Park, USA
VestasOnline Power Plant Controller	Vestas	Kennedy Energy Park, Australia; Terna Energy Park Power Platn; Greece; Lem Kaer HPP, Denmark
Hybrid Power Plant Controller	Vattenfall	Haringvliet HPP, Netherland
myPlant Energy Management	Innio group	District Heat & Electricity network, Rosenheim, Germany

3.2 Local asset control: advanced power electronic inverter innovations

Power electronic converters and inverters (often referred to as converters) that convert DC (direct current) electricity into AC (alternating current) electricity or facilitate voltage/current conversion are essential in applications ranging from renewable energy systems (such as solar panels and wind power plant) to electric vehicles (EVs) and industrial settings. With the growing demand for flexibility in power systems, the control features integrated into converters in photovoltaic (PV), wind and battery storage power plants, are driving significant innovations. On one hand, the development of new features aims to provide stability services traditionally offered by synchronous generators, such as frequency regulation, voltage control, and the ability to inject large currents during faults, along with inertia supply. On the other hand, new converter-specific features, like rapid generation ramping capability, are being explored to enhance flexibility. Key trends in smart inverter power control include:

DYNAMIC POWER MANAGEMENT AND GRID SUPPORT

- **Real-Time Power Adjustment:** Initially, PV and wind inverters inject the maximum power generated using MPPT (maximum power point tracking). Modern inverters[25] allow for rapid adjustments to active and reactive power output in response to changing grid conditions, such as variations in frequency and voltage. Without a storage system, only power reduction is

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[23] «Integrated energy and ancillary services optimized management and risk analysis within a pay-as-bid market», Applied Energy, vol. 371, p. 123628, oct. 2024, doi: 10.1016/j.apenergy.2024.123628.

[24] Zhu, R., Das, K., Sørensen, P.E. and Hansen, A.D. (2025), A Review on Energy Management System for Grid-Connected Utility-Scale Renewable Hybrid Power Plants. WIREs Energy Environ, 14: e70004. https://doi.org/10.1002/wene.70004

[25] P. G. Papageorgiou, P. T. Papafilippou, K. O. Oureilidis and G. C. Christoforidis, "An Adaptive Controller of a Hybrid Storage System for Power Smoothing With Enlarged Battery Lifetime," in IEEE Transactions on Sustainable Energy, vol. 15, no. 4, pp. 2567-2580, Oct. 2024, doi: 10.1109/TSTE.2024.3426917

possible, unless operating under maximum production power by default. In hybrid renewable energy (RE) systems, such as PV-storage or wind storage, bilateral regulation is possible. In these cases, inverters receive power setpoints from grid operators or higher-level control systems (EMS or PMS) and adjust their output accordingly.

- **Grid Frequency and Voltage Regulation:** Modern inverters can adjust their output to help stabilise grid frequency and voltage[26]. Despite the intermittent nature of PV and wind energy, power production can be controlled smoothly, especially when combined with accurate production forecasts and measurements. For instance, inverters help maintain grid stability by absorbing or injecting reactive power, preventing voltage or frequency fluctuations. Power-frequency or power-voltage (P(f)/P(V) or Q(f)/Q(V)) settings can be configured according to specific grid codes. However, the ability to regulate voltage and frequency is inherently constrained by the converter's apparent power rating. The provision of reactive power (Q) for voltage support reduces the capacity available for active power (P) injection. Also, although reactive power does not directly draw energy from internal storage elements (e.g., batteries or supercapacitors), its generation imposes additional thermal and electrical stress on the converter, potentially necessitating active power derating to ensure safe operation. Moreover, in systems with limited DC-link energy buffering, rapid variations in reactive power can induce significant voltage fluctuations, compromising control stability. These limitations underscore the importance of carefully managing the active–reactive power balance and internal constraints when designing converter-based grid support functionalities.

- **Power ramp rate control[27] :** This mode of operation limits changes of active power generation to a fixed value during any sudden increase in power availability. This is crucial to protect grid stability from possible overloads of network components and frequency excursions due to rapid changes in generation.

LOAD SHARING AND POWER COORDINATION IN DISTRIBUTED SYSTEMS

- **Distributed Inverter Systems:** In large-scale energy systems or microgrids, multiple inverters are often deployed to share the power generation load[28]. Power distribution among inverters is handled thanks to coordination control mode, allowing these inverters to work together and optimise overall system performance.

SMART INVERTERS FUNCTIONALITIES

- **The integration of the Internet of Things (IoT) and big data technologies** has made modern inverters smarter and more digitalised. They now feature real-time monitoring and remote-control capabilities, allowing users to check system performance through smart devices at any time.

- **Advanced monitoring and control functions** enable better management of renewable energy production, fault detection, predictive maintenance, and performance optimisation. Thanks to data availability and computing capability progress, advanced control techniques using AI such as Artificial Neural Network, MPC and deep learning are more and more proposed in R&D projects[29]. However, these methods often face limitations such as high computational complexity, limited adaptability to varying operational conditions, and challenges in real-time implementation on low-cost hardware.

GRID STABILITY SUPPORT, I.E. GRID FORMING

Grid-forming functions refer to an inverter's ability to manage grid frequency and voltage stability, providing inertia and short-circuit current during faults. Initially designed for remote or islanded power systems, grid-forming capabilities in inverters are increasingly being considered for integration into grid-tied renewable energy and storage systems. This shift is driven by growing recognition of their potential to enhance grid stability and by emerging requirements in various network codes. Ideally, inverters capable of operating alternately in grid-following and grid-forming modes, with smooth transitions between these modes, would offer additional flexibility to the system. Under normal conditions, renewable energy systems operate in grid-following mode through the inverter. However, if

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[26] U. Datta, A. Kalam and J. Shi, "Battery Energy Storage System Control for Mitigating PV Penetration Impact on Primary Frequency Control and State-of-Charge Recovery," IEEE Transactions on Sustainable Energy, vol. 11, no. 2, pp. 746-757, April 2020, doi: 10.1109/TSTE.2019.2904722

[27] S Maity, Z.H. Rather, S. Doolla, A comprehensive review of grid support services from solar photovoltaic power plants, Renewable and Sustainable Energy Review, Volume 210,2025,115133,ISSN 1364-0321

[28] Md Tonmoy Hossain, Md Zunaid Hossen, Faisal R. Badal, Md. R. Islam, Md. Mehedi Hasan, Md.F. Ali, Md.H. Ahamed, S.H. Abhi, Md. Manirul Islam, Subrata K. Sarker, Sajal K. Das, Prangon Das, Z. Tasneem, Next generation power inverter for grid resilience: Technology review, Heliyon, Volume 10, Issue 21, 2024, e39596, ISSN 2405-8440, https://doi.org/10.1016/j.heliyon.2024.e39596

[29] Maiworm, M., Gaussian process in control: model predictive control with guarantees and control of scanning quantum dot microscopy. 2021

necessary (e.g., in the case of grid disturbances), the system can provide grid-supporting services with active/reactive or inertia contribution. In extreme cases, those inverters can isolate themselves from the grid and operate locally as a microgrid, continuing to function independently due to the grid-forming capability. Grid forming inverters are majorly deployed on storage systems or hybrid RE-storage systems.

Inverter control schemes depend on grid service requirements (grid forming or grid following) and inverter topology. Ongoing innovations in inverter control focus on distributed and collaborative control strategies, which require algorithm development and robust communication infrastructure to integrate both real-time measurements and commands.

4 OVERVIEW OF PROJECTS ON RE FLEXIBILITY ON 2021-2026

44 EU projects related to flexibility for the power system topic have been analysed to provide an overview of ongoing solutions and development priorities on renewable energy (RE) flexibility supply within EU power system, as reported in Table 3. The analysis focuses on projects from 2021 and which end by 2026, ensuring the inclusion of recent results from completed projects and advanced insights from those still underway.

Table 3 - Projects on vRES flexibility (period: 2021-2028)

#	Project	Scope	End date
1	ACCEPT	EU-H2020	2024
2	AGISTIN	EU	2026
3	ALPGRIDS	EU	2022
4	BEFLEXIBLE	EU	2026
5	BD4OPEM	EU-H2020	2023
6	COLLECTiEF	EU-H2020	2025
7	domOS	EU-H2020	2024
8	eCREW	EU-H2020	2023
9	edgeFLEX	EU-H2020	2023
10	Efort	EU	2026
11	Elexia	EU (co-funding)	2026
12	EUniversal	EU	2023
13	FEVER	EU-H2020	2023
14	FLEX4FACT	EU	2025
15	FLEXGRID	EU-H2020	2022
16	FlexiGrid	EU-H2020	2023
17	Flexigy	National project	2022
18	FLEXIndustries	EU	2026
19	GIFT	EU-H2020	2023
20	GOFLEX	EU-H2020	2020
21	HEDGEIOT	EU-H2020	2027
22	HVDC-Wise	EU-H2020	2026

23	iBECOME	EU-H2020	2023
24	ICONIC	EU	
25	MERLON	EU-H2020	2022
26	pebbles	National project	2022
27	PHOENIX	EU-H2020	2023
28	piSCES	EU-Interreg	2021
29	Platone	EU-H2020	2023
30	RegEnergy	EU-Interreg	2022
31	RENergetic	EU-H2020	2024
32	RESCHOOL	EU	2026
33	REScoopVPP	EU-H2020	2023
34	Robinson	EU-H2020	2024
35	SINNOGENES	EU-H2020	2027
36	Sonder	EU-JPP SES	2022
37	SUDOCO	EU-H2020	2027
38	SYNERGIES	EU-H2020	2026
39	TWAIN	EU-H2020	2027
40	X-FLEX	EU-H2020	2023
41	WILLOW	EU-H2020	2026
42	ZellNetz2050	National project	2022
43	Maesha	EU-H2020	2025
44	LocalRes	EU-H2020	2026

4.1.1 Data collection methodology

A first selection of projects was gathered through the Flex-Community[30] and subsequently enriched with data from Cordis31. Various classification criteria were applied to structure the analysis:

- Project scale and level: projects span across multiple levels, from residential buildings to large-scale commercial and industrial renewable energy plants, and even grid utility scales, as can be observed in the bar chart of Figure 4 which shows project numbers share versus site spatial scale.

- Control innovation: a key focus is on digital solutions, including multi-level EMSs that integrate advanced control functionalities.

- Technology readiness level (TRL): all examined projects achieve a TRL of 5 or higher, with solutions implemented in real-world pilot sites. Solutions envisaged in industrial deployment are obviously one of the main criteria.

- Control-related innovations: the projects explore a diverse range of advancements, including EMS architecture (e.g., edge and

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[30] https://flex-community.eu/
[31] https://cordis.europa.eu/

cross-border control), digital tools (modelling, algorithms and digital twins), market frameworks (peer-to-peer platforms and energy community designs), control techniques (AI, blockchain, optimisation and data-driven approaches), smart meter integration (IoT-enabled systems, digital frameworks and advanced data acquisition), classified as in Table 4.

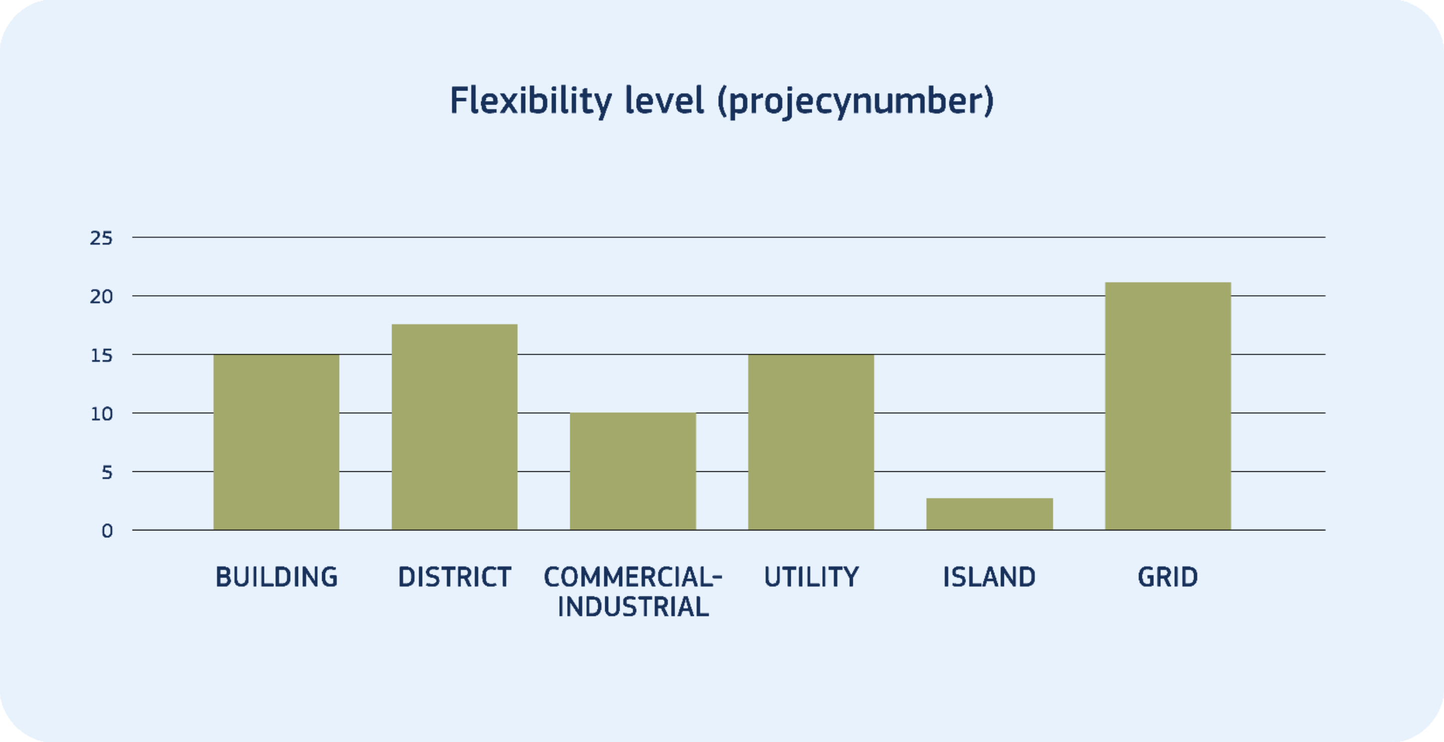

Figure 4 - Classification of flexibility projects according to site spatial scale

Table 4 - Control-related innovations in the examined set of projects, classified by main categories

EMS Control technic	• Multi-levels, cloud-edge • AI, blockchain, optimization, data-driven
EMS Tools	• Modelling, validation test • Digital twin • Grid simulation tools
Market	• Market design • P2P platform • Market platform
Data	• Data management • Communication standard • Forecasting • Smart meter
Others	• Aggregated EC • TSO-DSO coordination • IoT • EC platform

4.1.2 Analysis

The analysis highlights key trends and innovation priorities related to control solutions for renewable generation flexibility. In particular, nearly all projects emphasise the critical role of digital control technologies as foundational enablers of flexibility in renewable generation. These include dynamic EMS architectures capable of adapting to rapidly changing grid conditions, real-time optimisation of DERs, and data-driven approaches to flexibility aggregation, particularly for demand-response strategies.

Additionally, the development of advanced algorithms and optimisation tools plays a pivotal role in enhancing real-time decisions. Techniques leveraging machine learning and data-driven control are widely applied to improve system performance under variable renewable energy conditions. Additionally, the adoption of digital twins has become prevalent, offering powerful platforms to simulate, test, and validate control strategies across diverse scenarios before real-world deployment.

An increasing number of projects focus on multi-level and cross-border control solutions, addressing both TSO and DSO interactions, as well as localised grid challenges. Innovations in this area include predictive analysis for forecasting energy demand and generation, edge computing for decentralised control, and AI-enhanced EMS designs, all of which facilitate seamless coordination and operation of DERs across grid levels.

Energy communities and peer-to-peer trading platforms emerge as transformative components for unlocking localised flexibility potential. These solutions capitalise on blockchain technology to create secure and transparent energy trading frameworks, alongside digital marketplaces that enable active participation by prosumers. These platforms provide mechanisms for local energy trading and enhance the integration of decentralised renewable sources.

Finally, most projects emphasise deployment and scaleability, with many solutions achieving TRL 7-8, thus ensuring readiness for industrial deployment. Pilot implementations on multiple sites across Europe demonstrate the large-scale integration of battery storage systems, tools for flexibility aggregation, and advanced control frameworks designed to meet the requirements of both industrial and utility-scale applications.

In terms of control topics, the projects can be organised as shown in the tree-map chart of Figure 5. The map visualises the data collected from the project using nested and coloured blocks. The area of each block corresponds to the quantification of a specific control topic in proportion to the whole dataset of the analysed projects whilst the different colours are used to differentiate the control topics categories. Thus, larger rectangles mean the specific category has greater significance in the dataset.

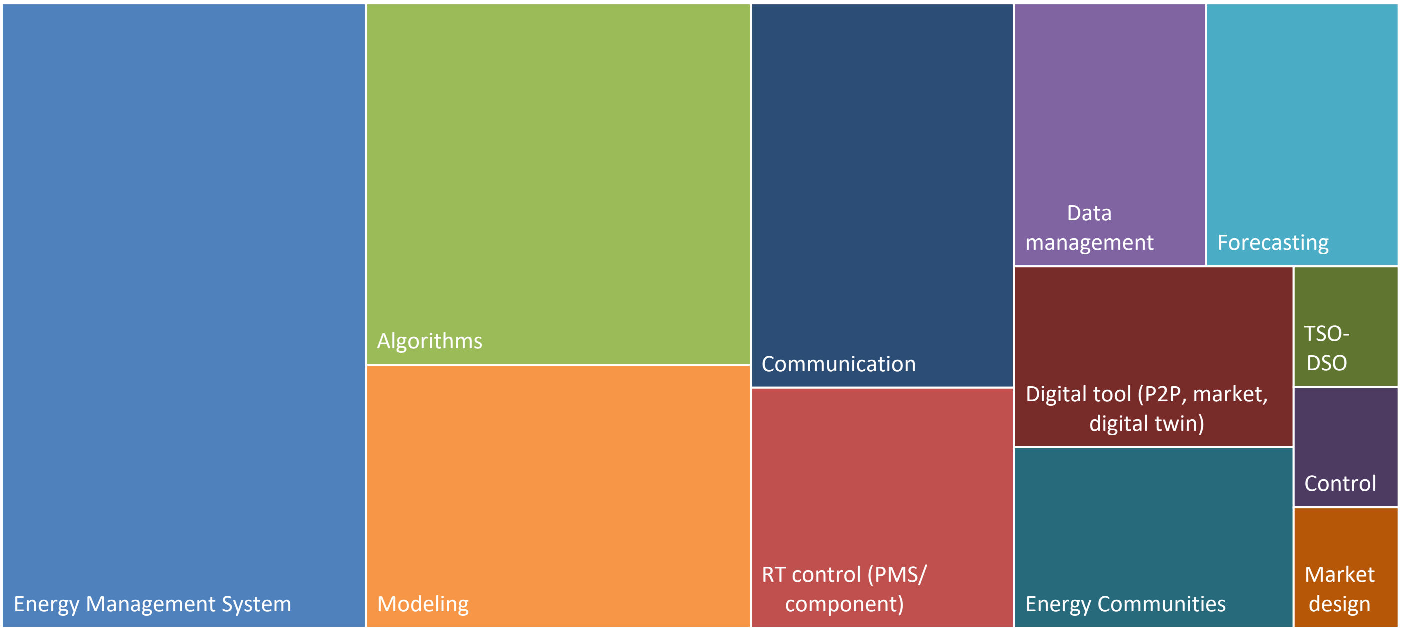

Figure 5 - Control topics investigated in the projects with the quantification of each topic investigation represented by the corresponding area larger

Figure 5 illustrates the emphasis placed on various control solutions within the selected projects of Table 3. The bloc sizes represent specific control-related innovations or methodologies across the project selection. As can be observed, the most prominent focus area in terms of flexibility across the project is EMS. This underscores the importance of dynamic and scalable EMS architectures in optimising the operation of DERs and ensuring grid stability. Advanced algorithms and modelling form critical components of these projects. This includes the importance of predictive analysis, optimisation techniques, and machine learning in enabling real-time decision-making and enhancing system reliability. Forecasting tools have a relatively good presence in the chart, indicating their role as control solutions. Communication frameworks and digital tools, such as peer-to-peer platforms and market systems, play a pivotal role in integrating decentralised systems and fostering energy communities; the focus on digital tools also reflects the growing importance of blockchain and IoT technologies. Continuing with energy communities, as can be seen from the graph, they show a growing trend towards localised energy trading and prosumer participation. Projects focusing on these aspects are likely exploring novel market structures and community-driven flexibility solutions. Finally, TSO-DSO coordination is less prominent but critical for ensuring seamless integration between transmission and distribution operators, particularly in multi-level control frameworks.

The following projects with case studies of MW-scale RE power plant are reported below and described with a more detailed analysis:

- **AGISTIN**[32]

The Advanced Grid Interfaces for Innovative Storage Integration (AGISTIN) project is an EU-funded initiative aimed at accelerating the deployment of renewable energy through the advanced integration of innovative energy storage technologies. Running from January 2023 to December 2026, AGISTIN focuses on developing advanced grid interfaces and control strategies to enhance EMS and inverter control.

Control Algorithms: The project is developing open-source control algorithms to coordinate energy storage, on-site generation, and end-use assets. These algorithms are designed to optimise the performance of the integrated system, providing flexibility and advanced grid services. In relation to the control techniques mentioned in the chapter 2, MPC is often applied to control the operation of energy storage systems (batteries or other types of storage) by predicting the demand and supply over a short-term horizon and adjusting the operation of the storage systems accordingly. In particular, MIPL optimisation technique is implemented to determine the optimal dispatch of energy storage systems and renewable resources in real-time while considering operational constraints (e.g., charging/discharging rates of batteries, grid limitations, etc.). DER coordinated control techniques are employed to optimise globally the operation of the various assets such as solar system, batteries and flexible loads. On inverter control aspects, grid-forming control strategies are employed to allow inverters to provide frequency regulation and voltage support, making it possible for the inverters to operate in isolated or low-inertia environments. Also, fast frequency response (FFR), based on inverters' high-speed dynamic power management to provide frequency regulation and voltage support, making it possible for the inverters to operate in isolated or low-inertia environments.

- **EdgeFLEX**[33]

EdgeFLEX was a European research and innovation project funded under the Horizon 2020 framework, running from April 1, 2020, to March 31, 2023. The project aimed to advance the concept of Virtual Power Plants (VPPs) to manage a broader range of distributed energy resources (DERs) and storage assets, thereby enhancing grid flexibility and supporting the integration of RES.

Traditional VPPs aggregate mid-scale DERs, such as solar, wind, and biomass, to enhance power generation and trade on electricity markets. EdgeFLEX expanded this model by enabling VPPs to offer both fast and slow dynamic control services, including real-time frequency stabilisation and voltage control. This was achieved through a novel architecture that used 5G-powered edge computing, allowing for near real-time communication and control of dispersed devices. A key innovation of EdgeFLEX was the development of a 5G application programming interface (API) to facilitate the connection and management of field devices, leveraging their flexibility. This development contributed to the adoption of three global mobile systems standards by the 3rd Generation Partnership Project (3GPP) during the project's duration. The project also introduced the concept of 'complex frequency', extending instantaneous frequency to the complex domain. This advancement enabled straightforward derivation of power system device models and controllers, particularly beneficial for power electronic converters—the building blocks of VPPs.

EdgeFLEX's outcomes were demonstrated through three field trials and accompanying laboratory tests, showcasing the platform's effectiveness in real-world scenarios. The project also explored innovative optimisations, financial tools, and business scenarios for VPPs, assessing their economic and societal impacts. By contributing to standards and European-level regulations, EdgeFLEX actively worked to remove barriers to the widespread adoption of its solutions.

- **FLEXIndustries**[34]

The FLEXIndustries project is an EU-funded initiative aimed at enhancing energy efficiency, flexibility, and sustainability in energy-

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[32] https://www.agistin.eu/
[33] https://www.edgeflex-h2020.eu/
[34] https://flexindustries.eu/

intensive industries. It focuses on integrating renewable energy sources, improving EMS, and enhancing inverter control strategies for better energy efficiency and grid stability. Predictive control algorithms for EMS are incorporated, where predictive algorithms help to anticipate energy demand and optimise energy consumption, allowing industries to shift their energy use to times when it's most beneficial, such as when renewable energy production is high. On the inverters side, FLEXIndustries focuses on advanced inverter control strategies, especially grid-forming and grid-following inverters. These strategies ensure that inverters can either support the grid (by following the voltage and frequency) or actively form the grid, providing stability in decentralised power systems or microgrids with high renewable energy penetration.

The project integrates energy storage systems with inverters to support better energy flow management thanks to coordination control. This enables industries to store excess renewable energy and release it during periods of high demand or low renewable energy availability, enhancing grid stability and operational efficiency. Moreover, inverters are equipped with advanced control strategies that allow them to provide frequency regulation and voltage support to the grid.

- **FLEXGRID**[35]

The FLEXGRID project focuses on medium to large-scale grid systems, aimed at accommodating high penetration levels of RES into electricity networks through innovative market mechanisms and advanced grid management systems. Among innovations in EMS, there are advanced market models, optimisation algorithms including optimal power flow (OPF) in order to consider grid constraint in energy dispatching decisions, PV and wind production forecasting, etc. Inverter control development by the project covers frequency and voltage regulation, and power factor correction, including both grid-forming and grid-following inverters. Coordination control is explored to ensure stable and efficient operation of a large number of inverters within the grid. In addition, improvements in communication protocols used by inverter to interface with EMS and other grid assets are evaluated and implemented aiming at interoperability standards and open protocols.

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[35] https://flexgrid-project.eu/

5 CONCLUSIONS AND FUTURE DEVELOPMENTS

In summary, the increasing flexibility needs driven by the integration of renewable and distributed energy resources have led to the development and deployment of holistic control systems, combining short-term (device-level), medium-term (subsystem-level), and long-term (system-level) control layers. These architectures are often supported by cloud-edge computing frameworks, which ensure real-time responsiveness at the edge (e.g., inverters, local controllers) and strategic optimisation in the cloud (e.g., EMS, coordination control). Current EMSs leverage a broad range of methodologies designed to multi-objectives optimisation while integrating forecasting, cyber-secure communication, and real-time monitoring.

At the local asset level, major innovations in inverter control enable new advanced features such as fast frequency and voltage regulation, ramp-rate control, coordinated load sharing, and even grid-forming behaviour that mimics synchronous machine inertia. Smart inverters increasingly incorporate AI algorithms, IoT connectivity, and adaptive control schemes, making them pivotal for achieving decentralised, flexible, and resilient energy networks. However, real-world deployment still faces several technical and organisational challenges determining future development prospects.

To ensure the successful integration of renewable energy and storage systems while maintaining grid stability and reliability, future activities must be structured according to different phases of system control progress. These activities align with the priorities outlined in PPC 1.2, PPC 2.2, PPC 4.1, PPC 4.2, PPC 4.3, PPC 6.1, and PPC 6.4 of ETIP SNET Innovation Roadmap, covering key aspects from control development to deployment and operation.

In the development phase, efforts should focus on advancing inverter control strategies to enable seamless integration of VRES while supporting grid stability by considering grid existing dynamics and components, including conventional power generations and loads. This includes the design and validation of adaptive/synthetic inertia and damping methods, ensuring that inverter-based resources contribute effectively to power grid imbalances. Additionally, accurate modelling approaches must be developed to simulate complex interactions between storage systems and the grid. Digital twin technology will play a crucial role in this phase, offering a real-time, data-driven approach to optimising control strategies and predicting system behaviour under varying conditions. Experimentation platforms, including hardware-in-the-loop (HIL) setups (e.g. power and controller HIL ones), will be essential for validating new control methods before large-scale deployment. These platforms should incorporate co-simulation capabilities that integrate power system dynamics with communication network constraints, ensuring a holistic assessment of different scenarios.

Once control strategies are developed and validated, the deployment phase must focus on establishing the necessary infrastructure to support widespread adoption. Smart metering technologies will need to be enhanced to provide real-time, high-resolution data on DERs, enabling more accurate prediction, monitoring, and control of grid conditions. The establishment of interoperability standards is also crucial at this stage, as ensuring seamless communication between storage solutions, renewables, and grid operators requires a standardised framework for data exchange. Communication protocol development should prioritise low-latency, high-reliability solutions that facilitate fast response times.

Finally, the operation phase must address the challenges associated with managing an increasingly digitalised and decentralised power system. Cybersecurity is already a concern and will become soon a critical concern, requiring the implementation of robust protection mechanisms such as blockchain-based energy transaction security and zero-trust architectures for grid communication networks. Ensuring resilience against cyber threats is essential, particularly as the number of interconnected devices and grid-edge computing applications continues to grow. Data forecasting will also play a fundamental role in maintaining system stability, leveraging artificial intelligence and machine learning techniques to predict renewable generation variability, load demand fluctuations, and optimal storage dispatch strategies. These forecasting models must be continuously refined and adapted using real-time data to support proactive grid management. Integrating AI models into forecasting and monitoring tools will further enhance grid operations, resiliency and support seamless integration of even more VRES. In parallel, efficient data storage and processing infrastructures must be deployed, incorporating decentralised storage solutions that enable secure and rapid access to critical energy data. Edge computing will also facilitate decision-making capabilities, reduce latency and enable real-time adjustments.

Concerning the power electronic converter control level, while technology has advanced significantly, several technical and regulatory gaps remain. In addition to ongoing progress in areas such as grid-forming capabilities, real-time control, AI-based algorithms, and scaleability in multi-inverter systems, further efforts are needed in regulatory alignment—particularly in standardisation and grid code updates—to enable the efficient integration of large shares of renewable energy.

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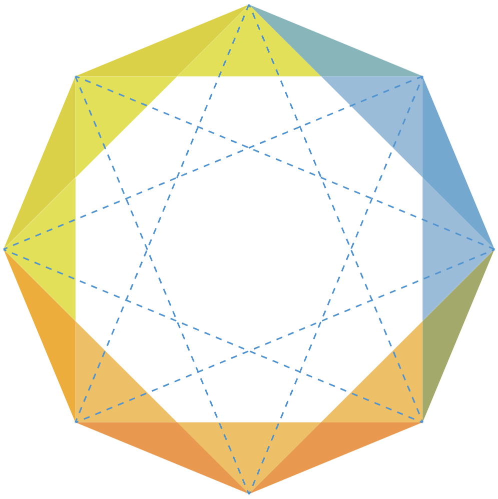

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