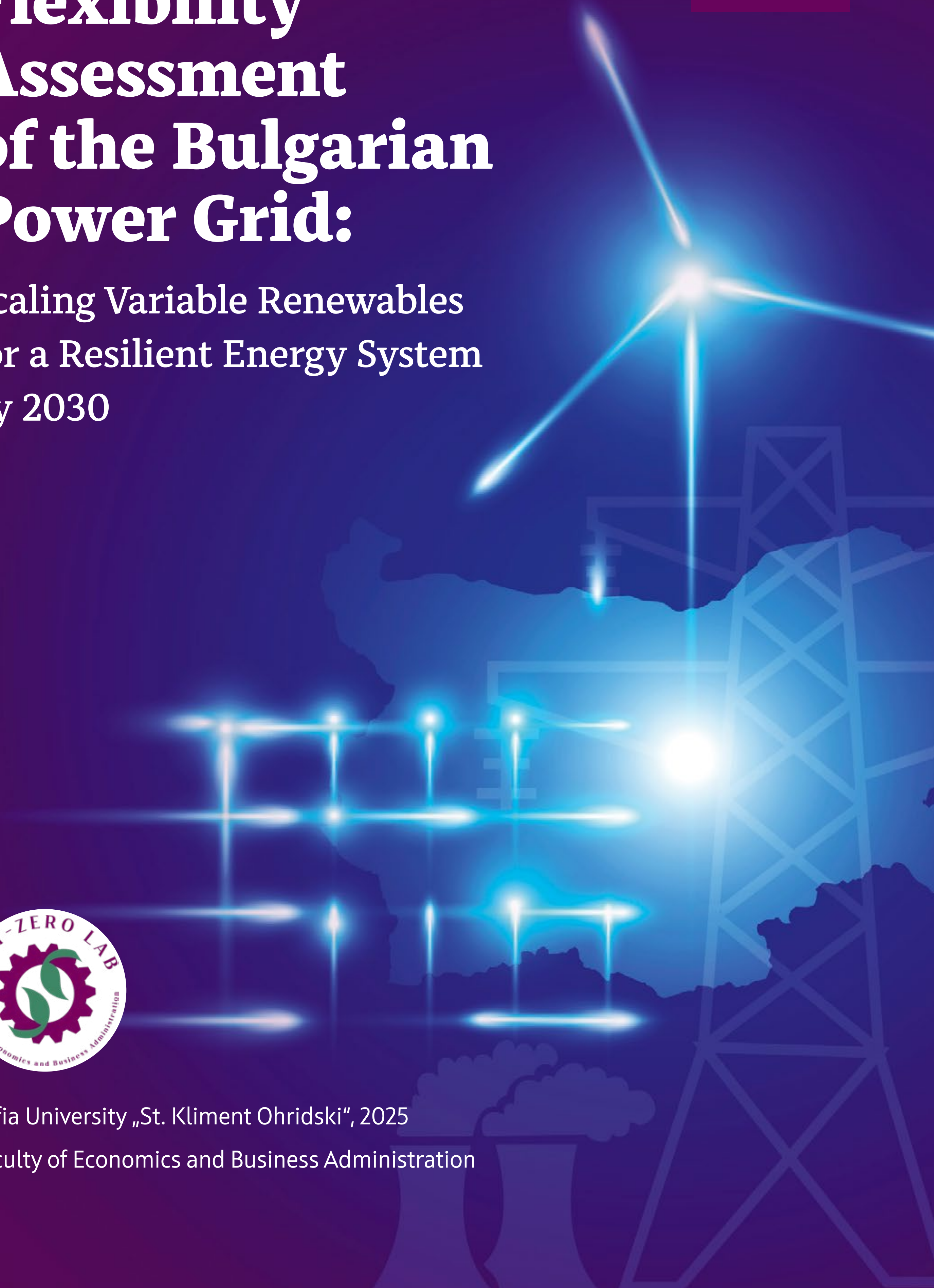
# Flexibility Assessment of the Bulgarian Power Grid:

## Scaling Variable Renewables for a Resilient Energy System by 2030



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# CONTENT

# LIST OF FIGURES

# NOTATIONS, ABBREVIATIONS, AND ACRONYMS

| | |
|---|---|
| **aFRR** | Automatic Frequency Restoration Reserve |
| **AI** | Artificial intelligence |
| **BEMS** | Building energy management system |
| **BEVs** | Battery Electric Vehicles |
| **BRP** | Balancing responsible party |
| **CHP** | Combined Heat and Power |
| **DR** | Demand Response |
| **DRG** | Distributed Renewable Generation |
| **DSO** | Distribution system operator |
| **ENTSO-E** | European Network of Transmission System Operators for Electricity |
| **ESO** | Electricity System Operator |
| **ESS** | Energy Storage Systems |
| **EV** | Electric vehicle |
| **FCEVs** | Fuel Cell Electric Vehicles |
| **FCR** | Frequency Containment Reserve |
| **FSP** | Flexibility service provider |
| **GDPR** | General Data Protection Regulation |
| **GW** | Gigawatt |
| **GWh** | Gigawatt hour |
| **HEMS** | House energy management system |
| **HPP** | Hydro power plant |
| **HPP** | Hydro Power Plant |
| **HVAC** | Heating, ventilation, and air conditioning |
| **Hz** | Hertz (Frequency Unit) |
| **IoT** | Internet of things |
| **IRENA** | International Renewable Energy Agency |
| **mFRR** | Manual Frequency Restoration Reserve |
| **ML** | Machine learning |
| **MW** | Megawatt |
| **MWh** | Megawatt hour |
| **NPP** | Nuclear Power Plant |
| **NTC** | Net Transfer Capacity |
| **PV** | Photovoltaic |
| **RES** | Renewable energy sources |
| **RES** | Renewable Energy Sources |
| **RR** | Replacement Reserves |
| **SSO** | Subsynchronous Oscillations |
| **TPP** | Thermal Power Plant |
| **TRM** | Transmission Reliability Margin |
| **TSO** | Transmission system operator |
| **TTC** | Total Transfer Capacity |
| **UCTE** | Union for the Coordination of Transmission of Electricity |
| **V2G** | Vehicle to Grid |
| **VRE** | Variable renewable energy |

# EXECUTIVE SUMMARY

The Bulgarian power system is undergoing an unprecedented surge in renewable energy deployment. Over the past four years, the country has significantly increased its solar capacity, reaching record-breaking growth in 2023 with an addition of **1,344 MW–the highest annual increase to date**–bringing the total installed solar capacity to **over 4000 MW by early 2025**.

With renewable energy installations, primarily onshore wind and photovoltaics, already exceeding 4.7 GW and continuing to grow, the Bulgarian transmission system is facing new challenges. These arise primarily due to the intermittent and low-inertia nature of wind and photovoltaic (PV) generation, which can introduce subsynchronous oscillations and frequency instability.[1] Unlike conventional synchronous machines, whose transient behavior and control strategies are well understood, new-generation renewable modules, based on power electronics and converter interfaces, require further study to assess their full impact on grid stability and system-level interactions. [2]

However, recent advancements in grid-forming inverters suggest that many of these stability concerns can be effectively addressed. Studies indicate that frequency stability can actually improve with the integration of grid-forming inverters, as they actively contribute to system inertia and voltage support. While challenges remain regarding the feasibility of an electricity system with an extremely high share of variable renewable energy (VRE) and the complete phase-out of synchronous generators, potential solutions such as synchronous condensers and other stabilization technologies could serve as a reliable backstop. As a result, while the transition toward high-VRE scenarios presents technical complexities, **ongoing innovations in power electronics and system stabilization strategies offer viable pathways to ensuring a secure and resilient power system.**

Ancillary services, such as frequency control and reserve capacity, are primarily provided by TPPs and reservoir-based HPPs. While wind and solar PV are at the center of Bulgaria's renewables expansion, their generation is inherently dependent on weather conditions, and battery storage remains insufficient for large-scale balancing. As a result, fluctuations in renewable output are primarily managed through hydropower adjustments, which pose balancing challenges, particularly during off-peak demand periods.

To address these emerging challenges, this study evaluates Bulgaria's power system under high renewable penetration, considering both **realistic developments based on current policies and techno-economic constrains as well as theoretical cases with unrestricted wind and solar expansion**. Using IRENA's FlexTool, the

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[1] Perera, U., Oo, A. M. T., Zamora, R. (2022). Sub Synchronous Oscillations under High Penetration of Renewables–A Review of Existing Monitoring and Damping Methods, Challenges, and Research Prospects. Energies, 15(22):8477.

[2] Dörfler, F. et al. (2019). Survey on the Control of Power Systems with High Penetration of Renewables. Renewable and Sustainable Energy Reviews, 115.

study assesses the **evolution of the generation mix, grid stability, curtailment risks, and economic feasibility to determine the most effective strategies for the energy transition**.

The results indicate a **substantial decline in coal-fired electricity generation, with reductions ranging between 48% and 61% compared to 2025 levels**. This transition is largely driven by the rapid deployment of VRE, particularly solar PV and wind power. While nuclear and hydro remain stable, with no additional capacity expected by 2030, wind and solar compete for grid integration. **A balanced combination of both proves to be the most cost-effective and system-reliable approach, with wind playing a more efficient role due to its higher capacity factor and ability to provide greater system stability.** In scenarios where wind deployment is capped at 2,500 MW (such as NECP 2030 and PV-limited cases), solar PV expands aggressively but at the cost of higher curtailment and system overcapacity. This highlights the importance of a diversified renewable mix, where wind complements solar, reducing inefficiencies and optimizing system performance.

The updated Bulgarian National Energy and Climate Plan (NECP) for 2030 is also modeled in this study. It presents an ambitious expansion of solar PV, leading to overcapacity and high curtailment rates exceeding 15% of annual VRE inflows. This highlights the grid's limited capacity to absorb large-scale solar production without additional flexibility measures. In contrast, the Unlimited PV scenario achieves over 30% VRE penetration while keeping curtailment below 5%, demonstrating the benefits of optimized dispatch strategies and more flexible system operation. The Chaira pumped storage plant plays an increasingly critical role in balancing excess renewable energy, reinforcing the need for expanded storage solutions to maximize the efficiency of VRE integration.

From an economic perspective, **all 2030 transition scenarios require an annualized system cost of €1.8–1.9 billion**, covering **investments in new generation capacity, operational costs, fuel expenses, $CO_2$ costs, and grid maintenance**. However, **renewable-dominated pathways prove to be more cost-effective than maintaining the current fossil-fuel-heavy system**, as they **replace costly fuel and carbon expenditures with long-term clean energy investments**. Among the scenarios, NECP 2030 incurs the highest total system cost, primarily due to overinvestment in solar PV capacity. While this scenario achieves the largest reduction in $CO_2$ costs, the high capital expenditure (CAPEX) required for excessive solar deployment outweighs these savings. A more balanced wind-solar mix proves to be a more economically viable strategy, ensuring both cost-effectiveness and system reliability.

The findings of this study emphasize the **urgent need for strategic planning in renewable energy integration**. **Grid reinforcements, grid forming inverters to enable operation at very low inertia levels, storage expansion, and improved system flexibility** (assessed in this study as hourly flexibility needs, not seasonal or daily) will be essential to accommodate higher shares of renewables while maintaining stability. **Wind energy should play a greater role**, as its **higher capacity factor and better complementarity with solar reduce the need for costly overbuilt PV capacity**. Moreover, **enhanced market mechanisms for flexibility services**, including **synthetic inertia, demand response, and storage incentives**, will be crucial in ensuring a reliable and resilient power system by 2030 and beyond.

**KNOWLEDGE BOX**

## Do you know the term Subsynchronous Oscillations (SSOs)? -

### Unwanted Electrical Vibrations in the Power Grid!

Think of a car driving on a bumpy road. If the bumps are at a certain pattern, the car may start to shake uncontrollably. In the electricity grid, a similar thing can happen with subsynchronous oscillations.

The electricity grid operates at a standard frequency (50 Hz in Europe, including Bulgaria).

SSOs occur when electrical equipment (such as wind turbines or solar inverters) interacts with the grid in a way that causes vibrations at lower frequencies (e.g., 10-40 Hz instead of 50 Hz).

These oscillations can damage power equipment, cause grid instability, and even lead to blackouts if they are not controlled.

**KNOWLEDGE BOX**

## Transient Behavior?

### The Power Grid's Reaction to Sudden Changes!

Imagine suddenly slamming the brakes in a car–there is a moment of instability before the car settles. In the power grid, transient behavior refers to how the system reacts to sudden changes, such as:

- A power plant suddenly shutting down;
- A large wind farm suddenly stopping due to weather changes;
- A fault or short circuit in the grid.

Power grids used to rely on big rotating machines (traditional power plants) that helped stabilize sudden changes. But now, as more renewables (which use power electronics rather than rotating parts) are added, the system's reaction to these events is changing, creating new challenges for stability.

**KNOWLEDGE BOX**

## Frequency Stability?

### Keeping the Power System in Sync!

Imagine a group of people jumping on a trampoline. If everyone jumps at the same rhythm, the trampoline stays stable. But if some jump at different times, it becomes chaotic. The power grid works the same way–all generators must work together at a synchronized frequency (50 Hz in Europe).

Frequency instability happens when electricity supply and demand are not balanced.

If there's too much power generation, the frequency rises; if there's too little, it drops.

Wind and solar energy fluctuate (e.g., clouds block the sun or wind speeds change), making it harder to keep the frequency steady. When the frequency goes too high or too low, it can cause power outages, equipment failures, and unstable grid operation.

# 1. INTRODUCTION

The energy sector is undergoing a tremendous transformation from a centrally located large fossil fuel-powered plants to numerous geographically dispersed renewable energy generators. This transition is characterized by a few trends which can be found in various stages and mixes in the different markets. They include decentralization, decarbonization, digitalization, democratization[3][4], and deregulation[5]. Each trend presents its own set of challenges to the existing system but also opens up a multitude of new opportunities.

**Decentralization** in the energy sector is primarily fueled by the exponential increase in the installation of renewable energy sources (RES) across the globe[6]. This surge is attributed to the decreasing cost[7] and the simplified installation processes of renewable technologies, particularly photovoltaic (PV) systems. The landscape of energy production is shifting from a model dominated by a few large-scale plants to one characterized by a widespread deployment of smaller, renewable energy assets. This phenomenon marks a stark departure from the traditional energy production paradigm and places the energy system at the forefront of adapting to the impacts introduced by renewable technologies.[8]

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[3] Vahidinasab, V., & Mohammadi-Ivatloo, B. (2023). Energy Systems Transition: Digitalization, Decarbonization, Decentralization and Democratization. Springer Nature.

[4] Asif, M. (2022). The 4Ds of Energy Transition: Decarbonization, Decentralization, Decreasing Use, and Digitalization. Wiley-VCH.

[5] Necoechea-Porras, P. D., López, A., Salazar-Elena, J. C. (2021): Deregulation in the Energy Sector and Its Economic Effects on the Power Sector: A Literature Review. Sustainability, 13(6):3429.

[6] IEA (2024), Renewables 2023. IEA, Paris. Licence: CC BY 4.0

[7] Way, R., Ives, M. C., Mealy, P., & Farmer, J. D. (2022). Empirically grounded technology forecasts and the energy transition. Joule, 6(9), 2057-2082.

[8] Hassan, Q. et al. (2024). The renewable energy role in the global energy transformations. Renewable Energy Focus, 48, 100545.

The integration of RES necessitates significant investments to accommodate the growing share of renewables within the energy mix[9]. This is where the concept of flexibility services becomes critically important.

> Flexibility services are defined in this report as a range of services offered by various stakeholders/technologies, which in response to certain signals–such as Distribution System Operators (DSOs)/ Transmission System Operators (TSOs)/ Balance Responsible Parties (BRPs) requests, market prices, or other indicators–alter their typical patterns of behavior/ schedules.

By leveraging flexibility, the immediate need for extensive investments in the energy infrastructure can be moderated[10]. Flexibility services allow for a more efficient management of the energy network by adapting energy production, consumption, and storage in response to demand and supply fluctuations. This adaptive approach enables the network to accommodate a higher penetration of renewable sources without the immediate requirement for substantial capital investments in new infrastructure.

**Decarbonization** is centered around climate actions and the fight against global warming. The increase in renewable energy is driven by the desire for lower emissions and reflects a collective aspiration for a more sustainable and environmentally friendly future[11]. The push for decarbonization is underpinned by several key international agreements, directives, and initiatives, each playing a vital role in shaping policies and strategies aimed at achieving a greener future. These include the United Nations Sustainable Development Goals (namely SG 7, 12 and 13[12]), the Paris Agreement[13], the European Green Deal[14], RePowerEU[15] as well as the Net-Zero commitments pledged by many countries.

These frameworks, along with various other European directives and national legislations, underscore the urgent need and drive for a transition to a zero-carbon economy. They collectively aim to mitigate the impacts of climate change, promote energy security, and drive economic growth through sustainable means.

**Democratization** signals the increasing role of consumers into the energy vertical, empowering them to have a more active role in energy markets. This trend is

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[9] G. Strbac, et al. (2015). It's All About Grids: The Importance of Transmission Pricing and Investment Coordination in Integrating Renewables. In IEEE Power and Energy Magazine, 13 (4), 61-75.

[10] L. Charpy, J. Lucas, S. Carloganu and G. Plattner (2021). Flexibility as a Cost-Effective Solution to Postpone Grid Investment: Request Guidelines And Ranking Of Proposals. CIRED 2021 - The 26th International Conference and Exhibition on Electricity Distribution, Online Conference, 2021, pp. 2730-2734, doi: 10.1049/icp.2021.1620.

[11] Papadis, E., & Tsatsaronis, G. (2020). Challenges in the decarbonization of the energy sector. Energy, 205, 118025.

[12] United Nations. Sustainable Development Goals.

[13] United Nations Framework Convention on Climate Change. The Paris Agreement.

[14] European Commission. The European Green Deal.

[15] European Commission. RePowerEU.

highlighted by the rise of "prosumerism"[16], where individuals not only consume energy but also produce it. For example, many households are installing small RES to power their needs, meanwhile buying deficit energy or selling excess back into the grid. Moreover, the emergence and growth of energy communities enhances this democratization process by fostering collective energy production and sharing practices, emphasizing sustainability and cooperation.

Simultaneously, this shift towards active participation of consumers is also facilitated by technological advancements in smart appliances and home energy management systems, enabling homes to become more energy-efficient and interconnected. Smart technologies allow individual consumers or aggregators to manage energy usage more effectively, contributing to the grid's flexibility[17]. This means that consumers can adjust their energy consumption based on real-time information about energy prices or demand, which not only leads to cost savings but also supports the integration of renewable energy sources by balancing supply and demand. The emergence of Battery Electric Vehicles (BEVs), Fuel Cell Electric Vehicles (FCEVs) and the ability for Vehicle-to-Grid (V2G) support will also have a huge impact on how energy systems are managed.

**Deregulation** is characterized by moving from regulated to liberalized market schemes. In a liberalized energy market, the potential benefits are twofold: on one hand, increased competition among suppliers/traders can lead to improvements in service quality and on the other hand, lower energy prices could be achieved due to market-driven pricing mechanisms[18]. There are however some challenges as well, which include ensuring fair market access for all participants and protecting consumers from potentially exploitative practices. Other regulatory adjustments may also be necessary to foster a more flexible and consumer-centric market, incorporating advancements in data protection (like GDPR), financial technologies due to micro-transactions (fintech), and mechanisms to enable more informed consumer choices.

**Digitalization**, sometimes referred to as digitization in the energy domain, is the process of making everything smarter and more connected. Lead technologies in this endeavor include Internet of Things (IoT), Artificial intelligence (AI), Machine Learning (ML), edge computing, etc.[19] Smartification is leading to concepts such as smart home, smart building, smart city, and energy community. Different software is also being developed to intelligently control energy usage and effectiveness. House energy management system (HMES) and Building Energy Management System (BEMS), just to name a few[20]. All in all, the integration of fast connectivity and AI advancements propels us towards a future where technologies can autonomously manage energy, reacting to market signals to consume, store, or sell electricity in-

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[16] Gough, M., et al. (2020). Prosumer flexibility: A comprehensive state-of-the-art review and scientometric analysis. Energies, 13(11), 2710.

[17] Perri, C., Giglio, C., & Corvello, V. (2020). Smart users for smart technologies: Investigating the intention to adopt smart energy consumption behaviors. Technological Forecasting and Social Change, 155, 119991.

[18] Halkos, G. E., & Tsirivis, A. S. (2023). Electricity Prices in the European Union Region: The Role of Renewable Energy Sources, Key Economic Factors and Market Liberalization. Energies 2023, 16, 2540.

[19] Singh, R., Akram, S. V., Gehlot, A., Buddhi, D., Priyadarshi, N., & Twala, B. (2022). Energy System 4.0: Digitalization of the energy sector with inclination towards sustainability. Sensors, 22(17), 6619.

[20] Khan, N., et al. (2022). Energy Management Systems Using Smart Grids: An Exhaustive Parametric Comprehensive Analysis of Existing Trends, Significance, Opportunities, and Challenges. International Transactions on Electrical Energy Systems, 2022.

telligently.

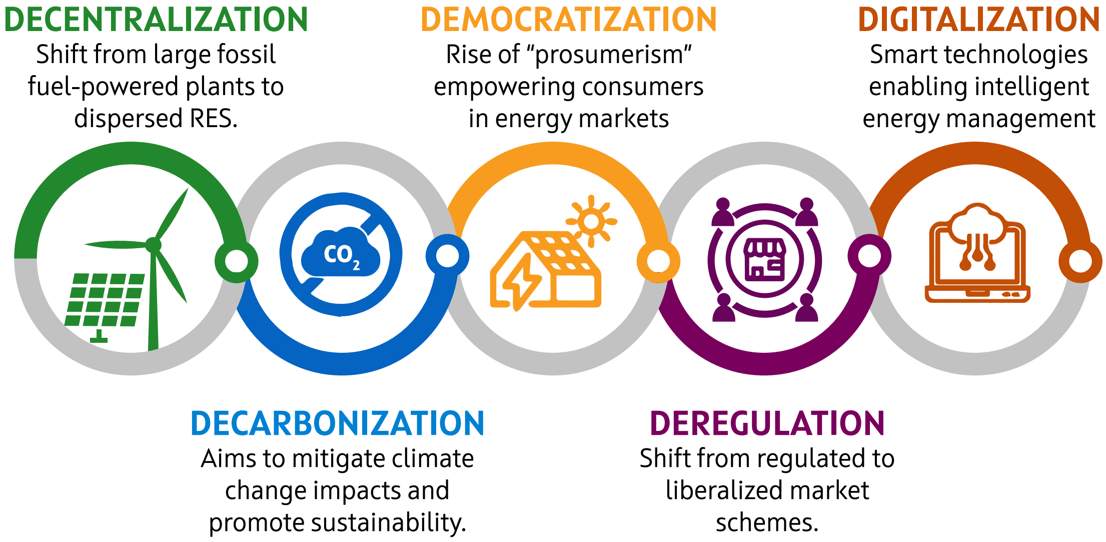

**Figure 1** TRENDS OF ENERGY SECTOR TRANSFORMATION

# 2. MAINTAINING POWER SYSTEM BALANCE IN BULGARIA'S ENERGY SYSTEM

Before delving into the scope and purpose of this study, it is important to understand its context within the broader power system control framework, which is briefly outlined in the following section.

**Frequency, voltage, active power, and reactive power are the main variables that TSOs monitor and control continuously to maintain power equilibrium in their electric systems 24/7/365**.

A range of comprehensive rules and standards, govern system operations, including the UCTE[21]/ENTSO-E Operation Handbook[22], the System Operation Guideline[23], Network Code on Requirements for Grid Connection of Generators[24], and ENTSO-E guidance document for national implementation for network codes on grid connec-

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[21] The Union for the Coordination of Transmission of Electricity (UCTE) was established in 1951 as a key organization responsible for ensuring the secure and reliable operation of the interconnected electricity grid across continental Europe. As one of the largest synchronous power grids in the world, operating at a frequency of 50 Hz, UCTE played a crucial role in maintaining stability, coordinating cross-border electricity exchanges, and setting operational standards for grid security. In 2009, UCTE transitioned into ENTSO-E (European Network of Transmission System Operators for Electricity), which now oversees all European TSOs.

[22] ENTSO-E. (2004). Operation handbook: Introduction (Version 2.5)

[23] European Commission. (2024). Regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation.

[24] ENTSO-E. (2013). ENTSO-E Network Code for Requirements for Grid Connection Applicable to all Generators.

European electricity transmission system, which is synchronously interconnected, operates at a set frequency of 50 Hz and must maintain a constant balance between active power generation and demand to avoid frequency deviations.

tion[25]. According to these regulations, the **European electricity transmission system, which is synchronously interconnected, operates at a set frequency of 50 Hz and must maintain a constant balance between active power generation and demand to avoid frequency deviations**. Any disturbance to this balance causes a frequency deviation from the setpoint[26], which is initially mitigated by the kinetic energy of synchronous rotating generators (used in TPPs, NPPs or HPPs and low-speed applications), or the physical inertia of rotating masses.

In the context of the ongoing energy transition, characterized by decentralization, grid modernization (smartification), and the increasing presence of Distributed Renewable Generation (DRG), **Energy Storage Systems (ESS) are emerging as potential enablers of greater flexibility**.[27] Nevertheless, except for hydro and pumped storage assets and considering the current national energy mix, **ESS is still a rather limited option for the Bulgarian power system to counterbalance such deviations as it implies massive deployment of powerful storage facilities** in the form of either coal, oil, water or hydrogen reservoirs or chemical energy carriers such as battery arrays. Such technologies do not yet suffice for real-time system balancing, which means that it is predominantly incumbent on generators to deliver adequate flexibility in terms of being capable of adjusting dynamically their power output.

A generator set must be able to respond instantly and at any time to demand fluctuations, as well as transmission or generation outages. This response should ideally occur without disrupting grid users. The ability to maintain this stability depends heavily on **inertia**, which plays a crucial role in regulating system frequency. Since frequency is directly tied to the rotational speed of synchronous generators, any shift in demand affects it–when demand increases, generator speed (and system frequency) drops, and when demand decreases, frequency rises. To correct these imbalances, **automatic primary control**–also known as **Frequency Containment Reserve (FCR)**–is activated within seconds. This mechanism restores balance between electricity generation and consumption, ensuring grid stability. The effectiveness of this response depends on the **total system inertia**, which helps absorb frequency deviations and smooth fluctuations. **A frequency deviation is therefore offset by the system total or equivalent inertia and the primary control action**[28]. It is critical that the system frequency is always kept in a strictly defined narrow limits. Without sufficient inertia, frequency variations become more pronounced, requiring faster and more frequent interventions from control mechanisms.

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[25] ENTSO-E. (2018). Network codes on requirements for grid connection: Implementation guidance document on frequency ranges.

[26] EURELECTRIC & ENTSO-E. (2011). Deterministic frequency deviations – root causes and proposals for potential solutions: A joint EURELECTRIC – ENTSO-E response paper.

[27] Showers, S. & Raji, A. (2019). Benefits and Challenges of Energy Storage Technologies in High Penetration Renewable Energy Power Systems. 209-214. 10.1109/PowerAfrica.2019.8928644.

[28] ENTSO-E. (2020). Inertia and rate of change of frequency (RoCoF). Version 17.

**System equivalent inertia** (**H**), measured in seconds, is a crucial factor in maintaining active power and frequency stability in the electricity grid. It represents how long the system can sustain its stored kinetic energy relative to its rated power output of synchronous machines. Inertia helps the system resist sudden frequency changes by temporarily absorbing imbalances between electricity supply and demand. The higher the inertia, the more stable the system remains during disturbances, reducing the risk of rapid frequency fluctuations.

Three levels of frequency and active power control are applied in the ENTSO-E synchronous area: Primary Control (FCR), Secondary Control

Three levels of frequency and active power control are applied in the ENTSO-E synchronous area: Primary Control (FCR), Secondary Control (automatic Frequency Restoration Reserve (**aFRR**) and manual Frequency Restoration Reserve (**mFRR**), and **Tertiary Control** (Replacement Reserves (**RR**). These represent system-wide mandatory reserve generation capacity categories of crucial relevance to supporting grid stability and resilience during unintentional frequency changes.[29]

**FCR** activation responds in seconds-timeframe before a frequency deviation exceeds ±20 mHz. Its objective is to maintain an equilibrium between generation and demand in the synchronous area. Based on concerted TSOs, FCR is responsible for the operational reliability and ensures that the system frequency is quickly stabilized following a disturbance or contingency. It is a fast-response reserve capability that does not restore the frequency and active power setpoints but only prevents them further deviation.

**FRR** uses a centralized and constant automatic generation control to adjust active power setpoints of generation units or dispatchable loads in the timeframe running from seconds up to 15 minutes after a contingency. It makes use of automatically regulated secondary control reserves and relies on an adequate availability of generation resources provided by electricity producers to TSOs. FCR and FRR operate independently and without interfering with each other.

**RR** involves automatic or manual changes in generator or load operational setpoints. It is tasked with ensuring that an adequate FRR is made available at the right time, allocating FRR power among generators in an optimal economic dispatch manner. RR acts by connecting and curtailing generation such as gas turbines, reservoir and PSPPs, stepping up or down generator outputs, redispatching generator modules involved in FRR, modifying the power interchange schedule, or performing load adjustments by means of centralized remote regulation or load shedding.

The logic of primary, secondary, and tertiary frequency control is illustrated in Figure 2:

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[29] EN ENTSO-E. (2009). ENTSO-E Policy 1: Load-frequency control and performance.

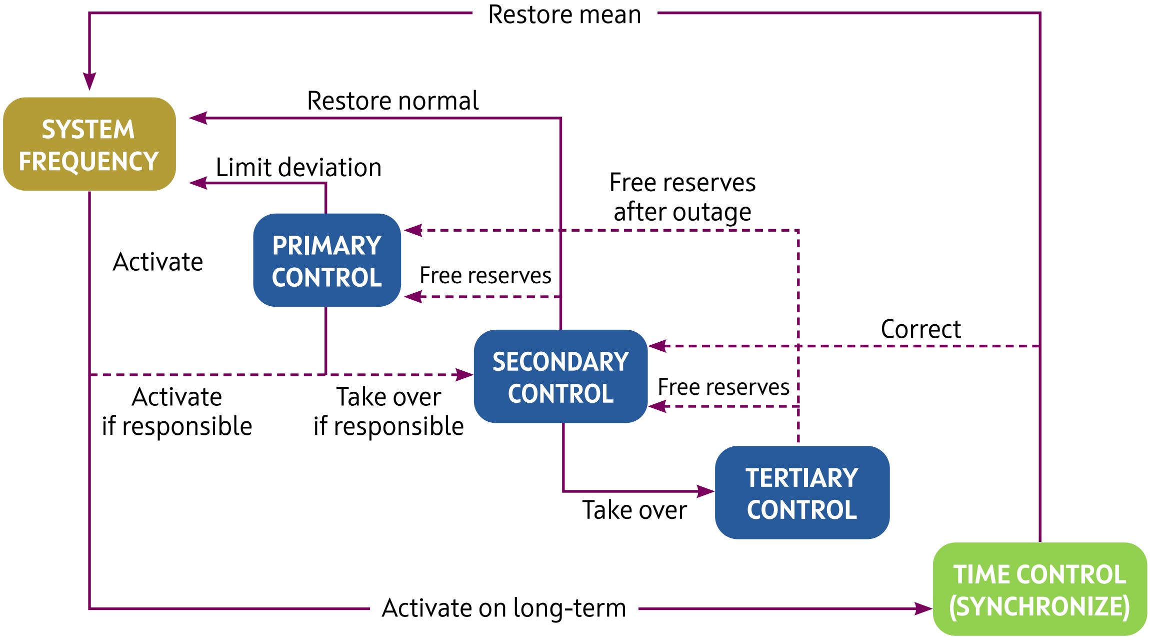

**Figure 2** **HOLISTIC ALGORITHM OF FREQUENCY CONTROL**

As renewables such as solar and wind park modules unfold in the energy mix, the system total inertia tends to decrease since, unlike rotating synchronous machines, inverter-tied RES do not produce physical inertia of system balancing relevance. To address this, **Synthetic Inertia**[30] **Technologies** such as grid-following and the emerging grid-forming inverters[31] are being developed and unfold. When looking at the power system control rules, one should also keep in mind security considerations such as the **N-1 criterion**, **Net Transfer Capacity** (**NTC**), **Total Transfer Capacity** (**TTC**), **Transmission Reliability Margin** (**TRM**), and **Reference Incident (RI)**.[32]

In specific terms of the UCTE Operation Handbook, the N-1 criterion stipulates that elements remaining in operation after failure of a single grid element (such as transmission line / transformer, generator or busbar) must be able to accomodate the change of load flows in the grid caused by that single failure.

TTC is the maximum exchange schedule between two adjacent controls areas that is compatible with operational security standards applied in each system if future grid conditions, generation and load patterns are precisely known in advance. TRM is a security margin to account for uncertainties on the calculated TTC values caused by unintentional deviations of physical flows during operation due to the physical functioning of Secondary Control, emergency inter-TSOs exchabge addressing unforeseen imbalances in real-time, and inaccuracies, e. g. in data collection and measurements. The NTC is calculated by subtracting the TRM from the TTC,

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[30] ENTSO-E. (2018). Need for synthetic inertia for frequency regulation: ENTSO-E guidance document for national implementation for network codes on grid connection.

[31] Pattabiraman, R. H. Lasseter. and T. M. Jahns, “Comparison of Grid Following and Grid Forming Control for a High Inverter Penetration Power System,” 2018 IEEE Power & Energy Society General Meeting (PESGM), Portland, OR, USA, 2018, pp. 1-5, doi: 10.1109/PESGM.2018.8586162.

[32] UCTE. Operation Handbook.

representing the maximum allowable power exchange between two areas while ensuring system security.

The RI is defined as the maximum instantaneous deviation between generation and demand, starting from undisturbed operation, in the synchronous area of ENTSO-E that the Bulgarian control zone belongs to. This may be caused by a sudden loss of generation capacity, load shedding / loss of load or interruption of power exchanges) and is to be countered by Primary Control. The RI is set to 3000MW and applies to the entire ENTSO-E synchronous zone.[33]

Apart from the above security constraints, TSOs are required to meet the 70% cross-zonal trading capacity minimum target pursuant to Article 16(8a) of Regulation (EU) 2019/943.

# 3. FLEXIBILITY SERVICES

## 3.1 Definition and types

The energy sector has long recognized the importance of flexibility. However, **the emergence of new technologies and smart grids is prompting a proactive approach to redefine the very nature of grid flexibility and the type of flexibility services that could be used.**

According to IRENA**, flexibility** is defined as *"the capability of a power system to cope with the variability and uncertainty that VRE generation introduces into the system at different time scales, from very short to the long term, avoiding curtailment of VRE and reliably supplying all the demanded energy to customers"*.[34]

On the other hand, Regulation EU-2024/1747 (EN – EUR-Lex, Art.2, (79)) states that *"flexibility" means the ability of an electricity system to adjust to the variability of generation and consumption patterns and to grid availability, across relevant market time frames. Thus, the concept of flexibility still lacks a unified definition* on **a broader scale,** and its availability varies significantly across different countries. These variations stem from differences in legislative frameworks, market structures, an grid requirements. As a result, while certain types of flexibility are regulated and actively implemented in some regions, they may be unavailable or unregulated elsewhere.

When discussing flexibility, it is essential to first understand what **flexibility services** mean in the current energy landscape and who can provide them. The concept varies across scientific literature and is implemented differently in countries with more advanced energy markets. To establish a shared understanding, we propose a broad definition that serves as a common reference moving forward: Flexibility services include a range of services offered by various stakeholders and technologies, which respond to certain signals (such as DSO/TSO requests, market prices, or other indicators) by altering their typical patterns of behavior/

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[33] ENTSO-E. (2009). ENTSO-E Policy 1: Load-frequency control and performance.

[34] IRENA. (2018). Power system flexibility for the energy transition, Part 1: Overview for policy makers.

schedules. These adjustments can affect energy consumption, production, or storage, and are made in exchange for certain incentives. These incentives might be financial (additional revenue, reduction in the electricity bills, differed investments in grid infrastructure), or non-financial benefits, like the attainment of green certifications of sorts. Having reached a common understanding, let's now dive into some of the most common types of flexibility and technologies, which can provide such.

As flexibility is a collective term used for different types of services, here are some of the most widely spread types of flexibility, which can be found:

**Demand Response (DR)**[35]**:** this involves adjusting (reducing or shifting) electricity use in response to grid signals, price incentives, or in emergencies. It helps balance demand with supply, particularly when the grid is under stress or during peak demand periods (appropriate for congestion management or improved grid balancing[36]).

**Load Shifting/Shedding**[37]: This involves moving energy usage from times of high demand to times of lower demand. It can also be defined as a type of DR, however unlike traditional demand side response, which may involve reducing overall energy use, load shifting is about changing when energy is used to better match renewable energy availability or lower electricity prices.

**Ancillary Services**[38]: These are services that support the transmission of electric power from producers to consumers and maintain the reliability of the grid. They include services like **frequency regulation, voltage control, and spinning reserves**. These services are often provided by resources capable of quick ramping or by energy storage.

When discussing flexibility, it is often categorized into explicit and implicit flexibility.

- **Explicit flexibility** refers to controllable loads and power sources that can be actively managed and quickly adjusted through external control. For example, a DSO may send a request to a PV producer to reduce its output or to an industrial facility to temporarily increase its electricity consumption to alleviate grid congestion.
- **Implicit flexibility**, on the other hand, is driven by behavioral adjustments and indirect control mechanisms. This type of flexibility typically involves smart appliances and automated systems that modify their energy usage based on price signals, demand-response incentives, or time-of-use tariffs.

Additionally, several barriers hinder the immediate and large-scale deployment of flexibility solutions in various markets. These challenges may arise from one or a combination of the following factors:

- **Technical limitations:** lack of advanced metering infrastructure, lack of appro-

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[35] McPherson, M., & Stoll, B. (2020). Demand response for variable renewable energy integration: A proposed approach and its impacts. Energy, 197, 117205.

[36] Stawska, A., et al. (2021). Demand response: For congestion management or for grid balancing?. Energy Policy, 148, 111920.

[37] Li, H., Wang, Z., Hong, T., & Piette, M. A. (2021). Energy flexibility of residential buildings: A systematic review of characterization and quantification methods and applications. Advances in Applied Energy, 3, 100054.

[38] Fernández-Muñoz, D., et. al. (2020). Fast frequency control ancillary services: An international review. Renewable and Sustainable Energy Reviews, 120, 109662.

priate software or control mechanisms;

- **Regulatory hurdles**: ambiguous or restrictive policies that do not fully support or even recognize the role of flexibility services;
- **Market challenges:** lack of standardized processes for valuing and trading flexibility, insufficient financial incentives for participants, high initial costs for setting up the necessary infrastructure;
- **Societal and behavioral barriers**: a significant knowledge gap among potential flexibility service providers and consumers regarding the benefits and possibilities of engaging in flexibility markets, need for targeted education and engagement initiatives to raise awareness and demonstrate the value of flexibility;
- **Data privacy and security**: detailed consumption data (falling under GDPR) required for effective demand response programs.

Navigating the path toward establishing flexibility markets presents both challenges and opportunities. Several European countries have already implemented such markets, offering valuable insights into best practices, regulatory adaptations, and effective integration strategies within existing energy systems. By leveraging these experiences, Bulgaria can adopt proven approaches to facilitate the deployment of flexibility solutions while minimizing potential disruptions. This strategy not only accelerates innovation but also supports a smoother transition toward a more resilient, adaptive, and future-proof energy system.

## 3.2 Stakeholders in the local flexibility market

Stakeholders in a local flexibility market can be categorized into direct and indirect participants, as illustrated in Figure 3.

### Direct Market Participants

Direct participants are those who actively engage in flexibility markets, either by procuring or providing flexibility services. The typical **procurers of flexibility services** include TSOs, DSOs and BRPs, in some scenarios the BRP can also be the DSO.[39] Their role is to ensure balance between demand and supply, thus simultaneously managing grid stability and reliability.

**Providers of flexibility services**, also known as Flexibility Service Providers (FSPs), include energy producers, consumers, prosumers, aggregators, and energy communities. These stakeholders leverage various technologies and strategies to offer different types of flexibility, either individually or by aggregating multiple sources to optimize grid performance.

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[39] Vagropoulos, S. I., Biskas, P. N., & Bakirtzis, A. G. (2022). Market-based TSO-DSO coordination for enhanced flexibility services provision. Electric Power Systems Research, 208, 107883.

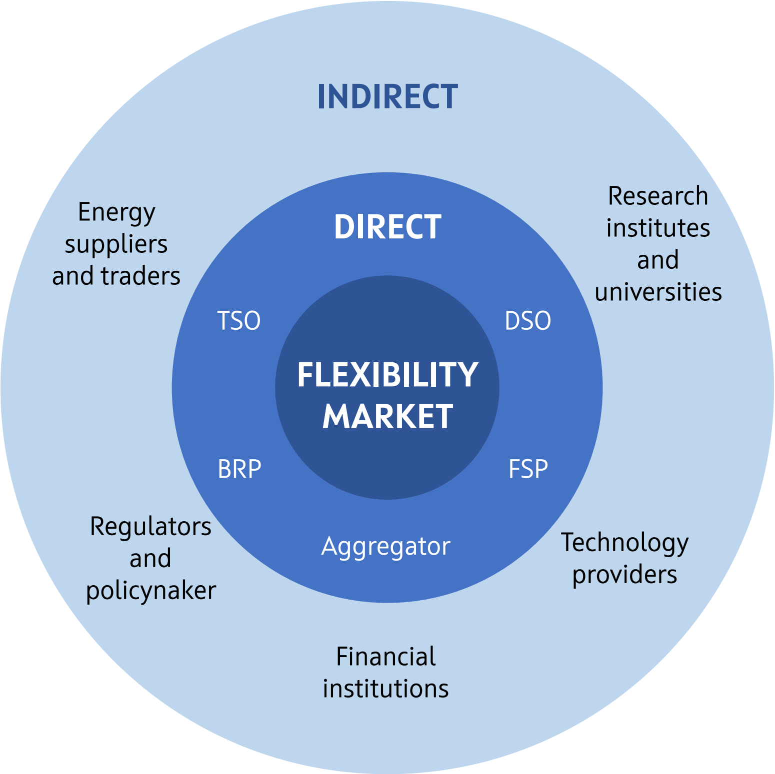

Figure 3. **FLEXIBILITY MARKET STAKEHOLDERS**

### Indirect Market Participants

When discussing indirect market participants, these include stakeholders who do not actively trade or provide flexibility services but play a crucial role in enabling, regulating, or supporting the flexibility market:

- **Energy Suppliers and Traders –** Support flexibility markets by offering clients demand response programs, aggregation services, and energy efficiency solutions, helping to optimize consumption and integrate more flexible energy management strategies.
- **Regulators and Policymakers –** Establish the regulatory framework necessary for the seamless operation of flexibility markets, ensuring transparency, fairness, and stakeholders' participation.
- **Financial Institutions and Investors –** Facilitate the digitalization of energy systems and the fulfillment of technical requirements needed to develop flexibility markets. They also provide financial support to help market participants engage actively in these new mechanisms.
- **Technology Providers –** Develop and supply essential hardware (such as smart meters, energy storage systems, and efficiency improvements in RES technologies) and software (including energy management platforms, flexibility market systems, billing integration, and user applications). These innovations enable the smooth operation of flexibility services.
- **Research Institutions and Universities –** Contribute to the advancement and innovation of flexibility markets by conducting research, improving market design, and developing smarter, more reliable, and user-friendly solutions.

## 3.3 Key Technologies for Grid Flexibility and Renewable Integration

The scientific and technological advancements in RES and other energy-related technologies play a crucial role in balancing supply and demand within the electricity grid. These innovations help accommodate the variability of renewable energy generation while enhancing grid stability and reliability. The choice of technologies used for flexibility varies based on several factors, including their operational characteristics, response time, duration of flexibility provision, capacity, and cost. Different solutions contribute to the overall system balance in distinct ways, ranging from fast-acting response mechanisms to long-term flexibility options.

Below is an overview of key technologies that enable flexibility, outlining their main performance aspects. While this list is not exhaustive, it highlights the most commonly referenced technologies in discussions on RES integration and grid flexibility:

- **Renewables**: their flexibility characteristics vary depending on the source. However, three fundamental aspects remain consistent: 1) **Flexibility is only available when the energy resource is present;** 2) **The extent of flexibility depends on the size of the power plant**, with larger facilities generally offering greater flexibility potential; 3) **The reaction time of RES is nearly instantaneous**, allowing for quick adjustments when needed. Below is a brief overview of the flexibility potential of hydropower, wind, and solar energy:
    - **Hydro power plants** have been used for balancing purposes for a while now, thus their flexibility potential is one of the best known and studied. The reaction time of both conventional and pumped HPPs is quite quick, being able to ramp up from zero to maximum output in a matter of munities. The duration of flexibility is dependent on the water availability and capacity of the plant, however generally it is thought that they can provide flexibility for a longer duration.
    - **Wind turbines** output is highly variable, as it depends on wind availability. However, with significant improvements in forecasting accuracy, wind power fluctuations can now be predicted and managed more effectively, allowing for adjustments in day-ahead and intra-day markets. The reaction time of wind turbines is almost instantaneous, enabling rapid changes in output when required. However, slight delays may occur depending on wind conditions and turbine control systems. To further enhance flexibility, ***some wind farm operators are implementing automated response systems that adjust turbine operation based on market signals***. For example, turbines may automatically shut down if electricity prices fall below their operational cost restart once prices exceed a predefined threshold. This development makes it easier for wind farms to actively participate in flexibility markets, dynamically adjusting their output in response to grid and market needs.
    - PVs generate electricity only when sunlight is available. While they cannot control solar radiation, they can adjust their output to some extent using advanced inverters and power electronics. However, their ability to provide flexibility is inherently limited to daylight hours and depends on weather conditions. A key challenge with solar energy is the high concentration of production around noon, which can lead to grid congestion or curtailment. Addressing this issue requires either changes in consumer behavior (shifting demand to peak solar hours) or new business models that optimize solar generation. One effective solution is coupling PV systems with battery storage, allowing energy to be stored and sold when demand and prices are higher, thus improving the overall value proposition of solar energy.

### EXAMPLE OF PV FLEXIBILITY IN PRACTICE

A notable **recent development in Bulgaria is the registration of the first PV provider of balancing services** by ESO, the national TSO.[40] Plans are underway to register two more, demonstrating that flexibility from RES is no longer a future possibility but a present reality.

- **BEMS/HEMS** are intelligent control systems designed to monitor and optimize energy consumption in residential homes and commercial buildings, respectively. These systems enhance energy efficiency, improve cost savings, and contribute to grid flexibility by responding to energy prices, demand-response signals, and user preference. By dynamically adjusting the operation of Heating, ventilation, and air conditioning (HVAC) systems, lighting, and other energy-consuming appliances HEMS and BEMS help reduce energy waste while maintaining comfort. Their response time can range from seconds to minutes, depending on the complexity of the required adjustments. The capacity of these systems to manage and optimize energy usage varies based on factors such as building size, the number of connected devices, and the integration of renewable energy sources and storage solutions. By leveraging smart automation, these systems play a key role in enabling demand-side flexibility, supporting a more sustainable and resilient energy system.
- **Batteries**, particularly in the context of EES, play a crucial role in providing flexibility. Their characteristics, including reaction time, duration, capacity, and specific features, make them essential components of modern energy systems. They are known for their near-instantaneous response, capable of starting discharge/charge within milliseconds to seconds upon receiving a signal. The duration of power supply depends on battery capacity and discharge rate, with some systems designed for short-term applications lasting minutes to hours, while others can provide flexibility over extended periods, ranging from several hours to days.
- **Electric Vehicles (EVs)** can function not only as a mode of transportation but also as a valuable source of flexibility, particularly when integrated with vehicle-to-grid (V2G) technologies. They can inject electricity back into the grid or adjust their charging rate within seconds to minutes, making them a responsive asset for demand response and ancillary services. The amount of energy an EV can supply depends on its battery capacity and state of charge; for instance, if a battery is 50% charged when discharging begins, it cannot inject more than that available energy. Typically, EVs support short- to medium-duration services, ranging from minutes to a few hours. Additionally, they can be programmed or remotely controlled to charge during periods of low demand or, as mobile assets, relocate to areas with grid congestion to optimize energy distribution and improve overall system efficiency.
- While not a standalone flexibility technology, **inverters** are essential components of the smart grid and play a crucial role in the renewable energy ecosys-

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[40] ESO. (2024). ESO registers the first RES producers as a provider of balancing services.

tem. They convert direct current (DC) from sources like solar panels and batteries into alternating current (AC), making the energy usable for electrical grids and household appliances. Their rapid response capabilities are vital for grid stability, providing support services such as reactive power control and voltage regulation. Equipped with smart technology, modern inverters enable seamless integration of energy storage, optimize renewable energy generation, and enhance overall grid resilience.

- To optimize grid operation and maintain stability, improved visibility and predictability of VRE generation are essential. Achieving this necessitates the development of a robust telecommunication infrastructure with low latency, high reliability and availability, and robust security standards. The evolution of next-generation cellular networks aligns well with this need.
    - 5G Capabilities: 5G offers significant advantages for the smart grid. Its millisecond latency enables real-time data exchange and faster responses to grid fluctuations. Additionally, 5G’s high device density facilitates a seamless and cost-effective integration of numerous sensors and devices within the grid.
    - 6G Potential: Looking ahead, 6G presents exciting possibilities. By potentially integrating artificial intelligence (AI) and machine learning (ML) directly into the network, 6G could enable even more sophisticated grid management strategies.

To back up and exemplify the above recommendations, the Smart5Grid project serves as a valuable case study demonstrating the practical application of 5G technology to enhance the integration of VRE within a smart grid. This project showcased millisecond-level precision in distribution generation monitoring and control through a real-world demonstration here in Bulgaria. The project utilized 5G to connect various RES facilities, including wind, solar PV, and hydro, to a dedicated network application. This application facilitated the collection of data from the connected RES with minimal latency (milliseconds) and 99.9% reliability and availability. Real-time access to this data enabled several key functionalities: real-time visualization, historical data tracking, alarm generation, and predictive maintenance enabler. This not only benefits the RES asset owner, but also Operation and Maintenance (O&M) team, TSO/DSO, Energy Traders and Balancing Service Providers. By applying 5G technology and enabling smarter RES assets, the Smart5Grid project demonstrates the potential for optimized performance and improved integration of VRE within the overall energy market.

This overview highlights key technologies that enhance grid flexibility, showcasing their interactions and contributions. While not exhaustive, it demonstrates the diverse ways flexibility can be supported. Each solution has unique benefits and limitations, and the choice of technology–or combination thereof–depends on grid requirements, regulations, and cost-effectiveness.

# 4. IRENA FLEX-TOOL ANALYSIS

## 4.1. Methodology and input data

This report presents an assessment leveraging the **IRENA FlexTool**, a free and open-source energy and power model, developed by **VTT Technical Research Centre of Finland Ltd.** for understanding the role of variable power generation in future energy systems and analyzing power system flexibility in RES-dominated energy systems. The tool was first introduced in 2018, accompanied by a policy overview and methodology report. A second version was released in April 2020, and the current third version became available in 2022, being contunously updated. The model leverages on a methodology that utilizes publicly available data.

This study examines the **2023/2024 state of Bulgaria's power grid**, analyzing installed generation and transmission capacities to identify potential **needs for grid reinforcement, storage solutions, or market adjustments**. The findings aim to support better decision-making, by informing regulatory refinements and market adaptations to accommodate a higher share of renewables by 2030.

While this assessment provides an initial analysis of flexibility potential, a more comprehensive approach may be required. As suggested by Carlos Fernandez at the *Webinar: IRENA FlexTool – Assessing power system flexibility for higher share of renewables*, incorporating additional analyses such as capacity expansion models, energy planning models, grid studies, and dispatch models would offer a more holistic understanding, guiding the development of a robust energy system and market strategy. Nevertheless, this initial flexibility assessment is a first step in analyzing the flexibility potential of Bulgaria's power grid.

For this assessment, data has been gathered from various **reliable sources** to populate the FlexTool with all necessary input parameters, generating insights into potential grid enhancements. **Annex 1** of this document details the input data and sources. The main entities to define a power system are explained on IRENA Flextool Github webpage:

- **Master**: includes parameters affecting the whole model such as $CO_2$ price, various types of penalties, times, durations, etc;
- **gridNode**: examines 18 grid nodes with their specific parameters;
- **Unit type**: defines selected unit types such as lignite, hard coal, nuclear, fossil gas, hydro RoR, hydro reservoir, pumped storage, wind onshore, solar;
- **Fuel**: examines the price and $CO_2$ content of available fuels (hard coal, lignite, natural gas, biomass, waste, uranium);
- **unitGroup**: defines groups of units (Fossil, Nuclear, Wind, PV, Hydro);
- **Units**: examines the parameters of units based on their node;
- **nodeNode**: examines parameters connecting different nodes.

The analysis of the data has yielded several insightful findings, which are presented in the following subchapter. Among them, some particularly notable results offer valuable insights into the flexibility potential of Bulgaria's power grid.

## 4.2 Scenario development

The analysis consists of two main scenario groups:

| | |
|---|---|
| **REALISTIC 2030 ALTERNATIVES**<br>These scenarios explore feasible developments by 2030, based on current trends, policy targets, and grid constraints. | • **Base Scenario** represents the current energy system (end of 2024) with a generation mix of hydro, fossil fuels (coal, gas, lignite), and moderate VRE capacity. The scenario is considered as a reference case.<br>• **NECP 2030** aligns with Bulgaria's National Energy and Climate Plan targets and energy mix capacities forecast for 2030 presented in the updated NECP version from January 2025, incorporating planned renewable energy expansion and fossil fuel reduction until 2030.<br>• **Unlim_PV** explores the scenario where the model optimizes photovoltaic investments to their maximum feasible level while capping wind capacity at 2,500 MW. This constraint reflects the current status of project development and the limited timeframe for implementation by 2030. Furthermore, the scenario makes it clear that PV expansion is allowed, but with certain limitations related to grid inertia and system stability (inertia limit kept at 15 GWs). |
| **THEORETICAL OPTIMAL SCENARIO WITHOUT CONSTRAINTS**<br>These scenarios assess the full VRE if no limitations (such as inertia, grid constraints, or economic barriers) were applied. | • **Unlim_PV_Iner** is similar to Unlim_PV, however the model releases the inertia limit and allows to maximum investment in solar energy.<br>• The **unlimited VRE scenario (Unlim_vre)** simulates a power system where wind and solar can be deployed freely, showing their theoretical cost-effectiveness. The key takeaway from this case is that **wind appears more cost-effective** than PV due to **higher variability in solar generation**–even though PV is cheaper, its limited generation hours reduce its optimal role in the system. However, this scenario still implies inertia limit kept at 15 GWs. |

## 4.3 Analysis of results

The analysis of scenario results and flexibility assessment focuses on key parameters that define the evolving energy system's performance, reliability, and economic feasibility. Each aspect provides insight into how different configurations of generation and system flexibility impact the overall energy transition. The **generation and consumption balance** examines how various energy sources contribute to meeting electricity demand. This analysis highlights the interplay between conventional and renewable generation, ensuring that supply aligns with consumption patterns and minimizing reliance on backup power or imports.

As renewable energy deployment increases, the **share of variable renewables and curtailment** becomes a crucial metric. **Energy curtailment refers to a controlled**

**turn off (deliberate reduction) of power systems in cases where there is system imbalance due to 1) excess supply or 2) transmission constraints.** Decreasing production deliberately is done to balance supply and demand as well as to enhance grid management (be it for solving congestion, restoring frequency, etc.).

A high share of solar and wind power indicates significant progress in decarbonization, but excessive curtailment–where renewable electricity is wasted due to grid constraints or insufficient flexibility–signals inefficiencies that must be addressed.

> Energy curtailment refers to a controlled turn off (deliberate reduction) of power systems in cases where there is system imbalance due to 1) excess supply or 2) transmission constraints.

The **daily generation profile** examines how the power system adapts to higher renewable penetration over specific periods, including information about the generation mix contributing to the overall electricity supply at different points in time. A snapshot of hourly generation during a spring week has been chosen to assess system flexibility under conditions that are neither extreme nor average but reflective of an evolving energy mix. In Bulgaria, spring is particularly insight-ful due to high solar generation, moderate demand, and nuclear maintenance schedules. Longer daylight hours lead to peak photovoltaic production, while demand remains lower than in winter (when heating dominates) and summer (when cooling loads peak). The interplay of these factors makes spring an ideal test case for analyzing curtailment risks, reserve capacity, and the role of flexibility solutions like pumped storage and demand-side management.

With a growing share of renewables, system stability challenges emerge, particularly in terms of inertia and reserve capacity. Traditionally provided by synchronous generators like coal, gas, and hydro, inertia helps maintain frequency stability. As these sources decline, alternative solutions such as synthetic inertia from battery storage, demand response or new market-based reserve mechanisms must compensate to prevent system instability. Synthetic inertia or **synthetic inertial response** refers to the provision of additional electrical power from a source that does not naturally store and release kinetic energy as its terminal frequency changes but instead emulates the response of a rotating mass.

There is **no single universal threshold for critical inertia**, as it depends on the specific grid configuration, interconnections, and reserve mechanisms. However, general guidelines and empirical studies suggest that **when system inertia drops below a certain level, the risk of instability increases significantly.** Based on the inertia constraint simulations conducted by Mehigan et al.[41] for two ENTSO-E decarbonization scenarios, the following conclusions have been drawn:

- **Large, well-connected power systems** in continental Europe can operate with **inertia above 15–20 GWs**, as they have strong interconnections and reserve mechanisms.
- **Isolated or weakly connected grids** typically require **higher inertia (above 25–30 GWs)** to maintain stability.

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[41] Mehigan, L., et al. (2020). Renewables in the European power system and the impact on system rotational inertia. Energy, 203, 117776.

- **Below 10 GWs**, most large power systems **enter a high-risk zone**, where frequency deviations become too rapid for conventional balancing mechanisms to correct.

For Bulgaria, the critical inertia threshold is estimated to be around 12–15 GWs

**For Bulgaria, the critical inertia threshold is estimated to be around 12–15 GWs**, below which the risk of frequency instability increases significantly.. Below this, the system faces higher risks of instability unless additional fast-response flexibility mechanisms (such as synthetic inertia from wind farms or advanced battery storage) are implemented. Therefore, scenario Unlim_PV_Iner assumes an inertia limit of 15 GWs**.**

As the **first line of defense in frequency regulation**, FCR plays a crucial role in preventing cascading failures and blackouts. FCR is the fastest-acting reserve, activating within seconds (typically within 30 seconds) when system frequency deviates from its nominal value (50 Hz in Europe). It operates continuously, ensuring immediate stabilization before slower reserves, such as Frequency Restoration Reserve (FRR), take over.

**FCR Up** refers to the provision of additional power when frequency drops below 50 Hz. Maintaining sufficient FCR Up ensures that the system can quickly compensate for sudden frequency declines caused by increased demand, unexpected generator outages, or fluctuations in renewable energy output. Without adequate FCR Up, the grid risks instability, requiring emergency interventions such as load shedding to prevent system-wide failures. In the modeling framework, downward FCR was excluded from the simulation based on the assumption that its procurement cost is negligible in high VRE penetration systems.

Additionally, slower reserves, which are typically used to manage forecast uncertainties and deviations from scheduled dispatch, were not explicitly represented in the model. This decision aligns with the real-time dispatch focus of the simulations, where such reserves are activated dynamically as needed rather than withheld in the optimization process. By omitting slower reserves, the model remains consistent with real-world system operations, ensuring that the optimization accurately reflects real-time balancing decisions without preemptively constraining available capacity.

**Finally, the total system cost** evaluates the economic feasibility of different energy pathways. This metric accounts for capital investments in new generation and storage, operational costs of dispatchable plants, and potential financial penalties associated with curtailment or system imbalances. A scenario may achieve high renewable penetration, but without economic viability, it risks being unsustainable in the long run.

Together, these parameters provide a comprehensive assessment of the trade-offs between sustainability, reliability, and cost-effectiveness. By evaluating how the energy system evolves under different scenarios, this analysis informs policymakers and system operators about the necessary infrastructure investments, regulatory adjustments, and market mechanisms required for a successful transition to a more flexible and resilient power system.

### 4.3.1. Generation/ Consumption of Variable Renewables

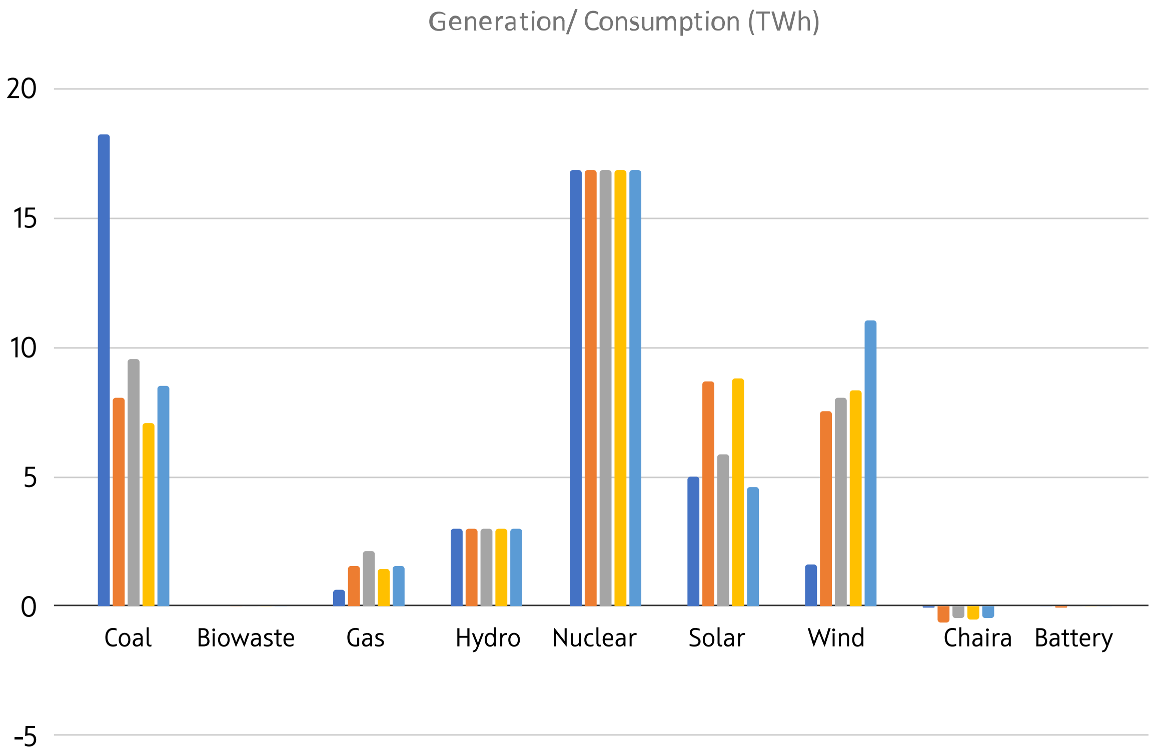


**Figure 4:** FLEXTOOL MODELING RESULTS. GENERATION AND CONSUMPTION ACROSS SCENARIOS

The transition to a low-carbon power system is evident across all modeled scenarios, with a **substantial reduction in coal-fired electricity by 2030**. Compared to 2025, the decline ranges between **48% and 61% across the four scenarios**, marking a significant step toward decarbonization. This shift reflects not only climate policies but also demonstrates declining lignate competitiveness due to increasing renewable penetration.

While coal generation declines, **nuclear and hydro output remain stable across all scenarios**. These technologies continue to provide **a baseload supply**, with no anticipated capacity expansions in the short five-year horizon. Their historical contribution is preserved, ensuring continuity in electricity generation amidst broader system changes.

A key differentiator across the scenarios is the **growth in solar and wind generation**. Solar expansion is particularly prominent in the NECP scenario and in the case of unrestricted PV deployment without inertia limitations, leading to a 75% increase in photovoltaic generation. However, when wind capacity is allowed to exceed the 2500 MW limit set by NECP, its contribution to domestic demand rises significantly, offsetting around 60% of the additional solar expansion. **This highlights the better complementarity of variable renewable energy sources, while also underscoring the strong competition between solar and wind for grid integration.** The higher capacity factor of wind energy allows it to displace a larger share of fossil fuels and other VRE, making it a dominant contributor to the mix when deployment constraints are lifted.

Beyond generation, **storage and flexibility solutions play an increasingly important role** in managing system variability. **PSHP Chaira acts as a critical balancing asset, absorbing excess renewable generation and releasing energy during peak demand periods**. **Battery storage, by contrast, is only deployed in the NECP scenario,** with **a net storage consumption of** -60 GWh, as its inclusion was mandated by the plan rather than being optimized by the model.

Chaira pumped storage hydropower plant acts as a critical balancing asset, absorbing excess renewable generation and releasing energy during peak demand periods. Battery storage, by contrast, is only deployed in the NECP scenario

While batteries have the potential to enhance grid stability through various ancillary services, the model accounts only for their role in providing FCR-Up, leaving other possible contributions unassessed. Given their presence in the system, batteries were primarily utilized for arbitrage rather than actively supporting grid stability. However, the extent to which they were actually used for FCR-Up remains uncertain. The "Lines" category represents internal transmission losses within Bulgaria, modeled at the transmission level using an 18-node network representation..

## 4.3.2. Share of Variable Renewables and Curtailment

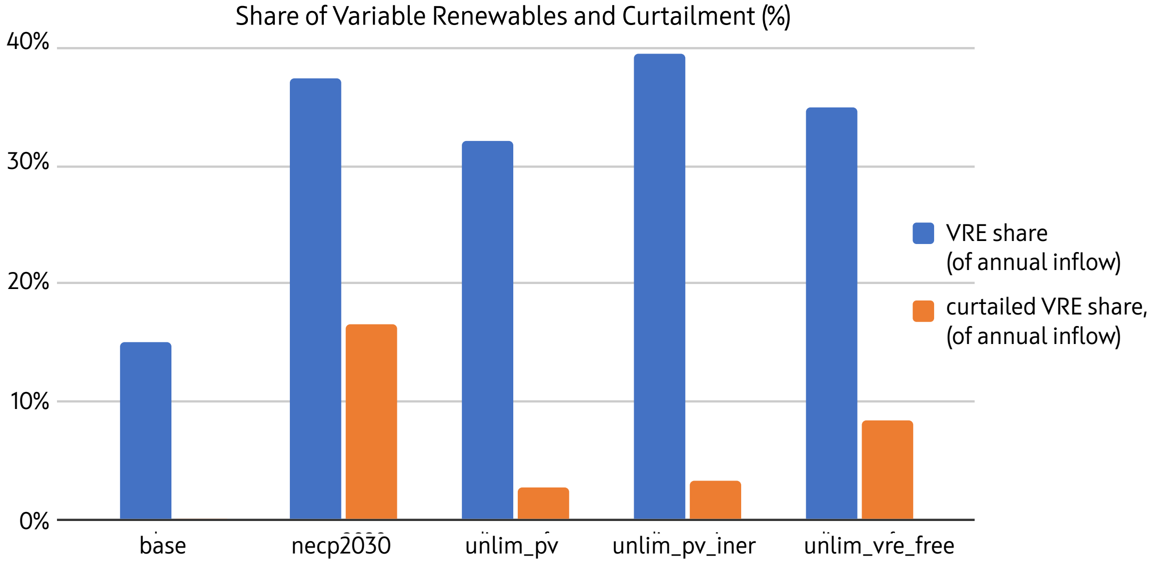


Figure 5: **FLEXTOOL MODELING RESULTS.
SHARE OF VARIABLE RENEWABLES AND CURTAILMENT ACROSS SCENARIOS**

**Across all scenarios, there is a more than twofold increase in the share of VRE** compared to the base scenario, signaling a significant shift towards a renewable-dominated electricity mix. For all the scenarios the VRE share is calculated after curtailments.

A key factor contributing to over 15% curtailment of the annual inflow is the inertia limit, which necessitates the continued operation of thermal generation, restricting the system's ability to integrate additional VRE.

In contrast, the Unlimited PV scenario successfully achieves over 30% VRE penetration while keeping curtailment below 5%. This indicates that removing certain constraints on PV deployment allows for a more balanced integration of CLEAN energy. The significantly lower curtailment suggests that a well-managed expansion of PV, likely combined with flexibility measures, enhances the efficiency of renewable utilization. The installed PV capacity in the Unlim_PV scenario is lower than in NECP 2030, as the model determined that expanding PV capacity due to the levels proposed in NECP 2030 would not be economically optimal to high levels of curtailment, which diminish the marginal value of additional PV capacity. Then, in Unlim_PV_iner, the model sees the value of more PV since the inertia limit is no longer and it does not need to curtail that much.

Scenarios with higher curtailment levels underscore the need for storage solutions, better grid planning, and enhanced cross-border electricity exchanges to ensure that the increasing share of renewables is effectively utilized. Moreover, the trade-offs between high VRE targets and curtailment must be carefully managed, as increasing renewable penetration without sufficient flexibility mechanisms can lead to energy inefficiencies. Additionally, enabling system operation at very low inertia levels is crucial to maintaining grid stability in high-renewable scenarios. This can be achieved through advanced technologies such as grid-forming inverters, which enhance system resilience by providing synthetic inertia and supporting frequency stability in the absence of conventional synchronous generation.

## 4.3.3. Changes in daily generation profile

The analysis of hourly generation profiles for one spring week across different scenarios provides key insights into how Bulgaria's electricity system adapts to increased renewable energy integration during periods of reduced consumption. Across all scenarios, the demand curve remains consistent, fluctuating between 3TWh/h and 6TWh/h.

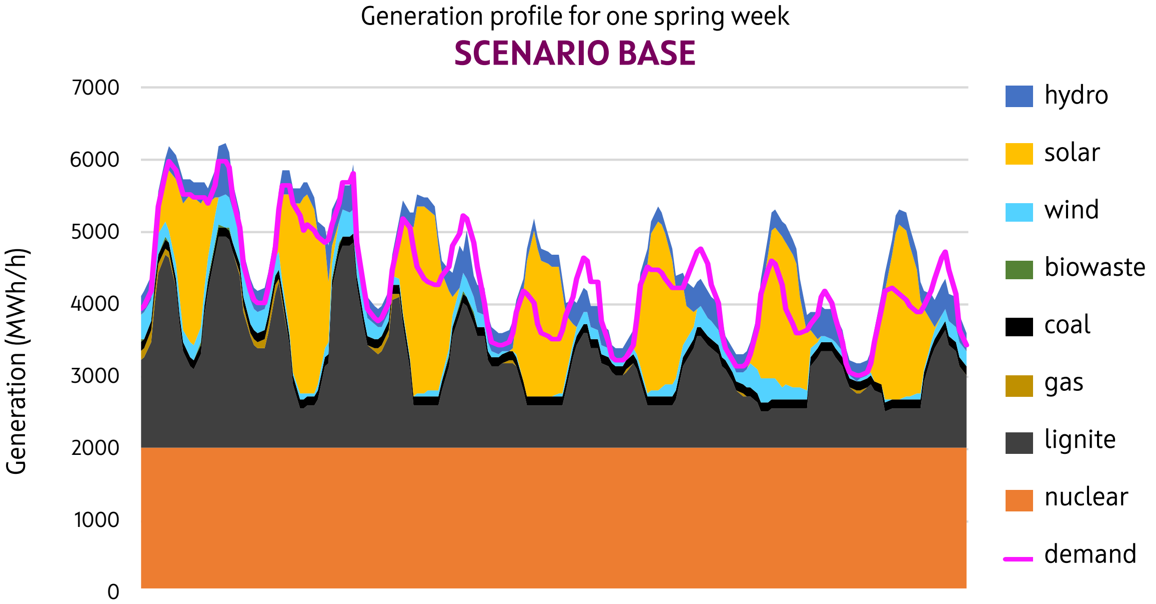


**Figure 6: FLEXTOOL MODELING RESULTS. GENERATION PROFILE FOR ONE SPRING WEEK IN THE BASE SCENARIO**

In the Base Scenario, lignite and nuclear power remain the dominant sources of electricity, with natural gas playing a minor, supportive role. Dispatchable sources provide the backbone of grid stability, while hydropower contributes flexibly to balancing daily variations. Wind energy's contribution remains modest, while solar power reaches a maximum coverage of 57–58% for only 2–3 hours on the sunniest days. This scenario reflects the current state of Bulgaria's electricity system, where fossil fuels still dominate, and VRE penetration remains limited.

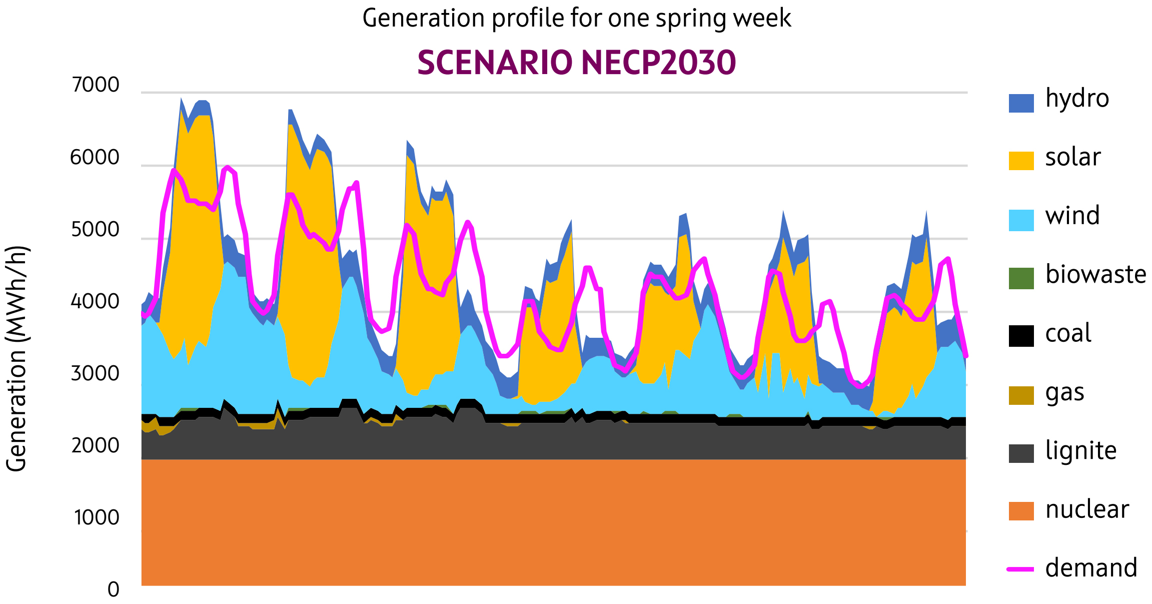
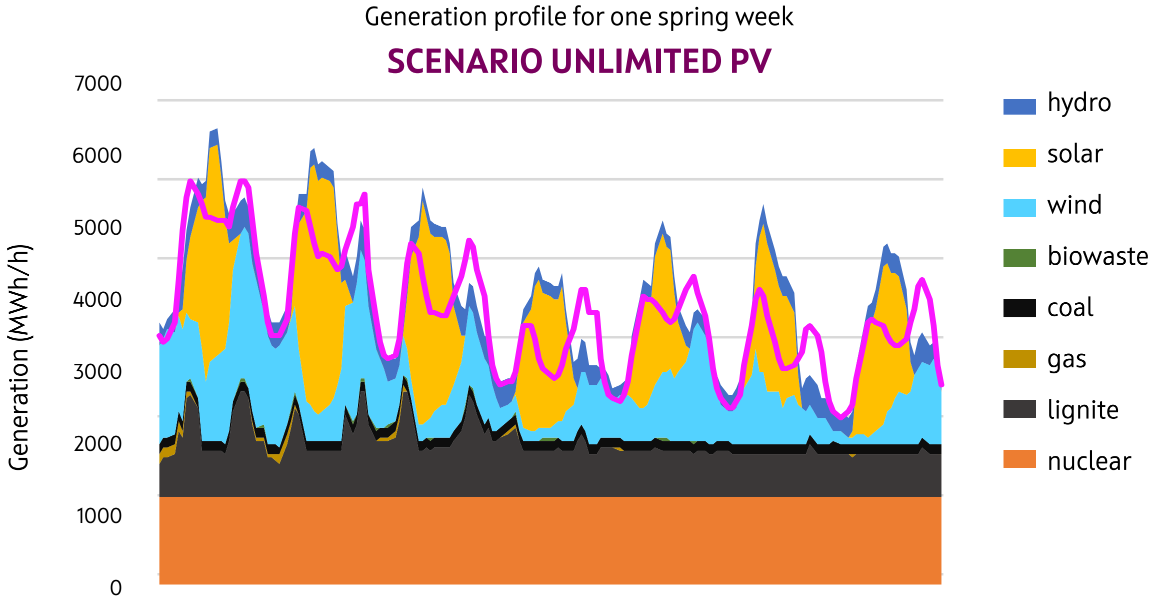


**FIGURE 7: FLEXTOOL MODELING RESULTS. GENERATION PROFILE FOR ONE SPRING WEEK IN THE NECP SCENARIO**

Moving to the NECP 2030 scenario, which assumes 6.8 GW cumulative installed capacity of PV and 2 GW of wind, the picture changes dramatically. On average, PV covers more than 55–60% of demand for 7 hours per working day and over 30% on weekends, when the electricity consumption is relatively lower. However, this increased solar penetration leads to high curtailment, exceeding 15% of annual VRE inflows, as the system struggles to absorb excess generation due to grid limitations and the rigidity of conventional power sources maintaining system stability.

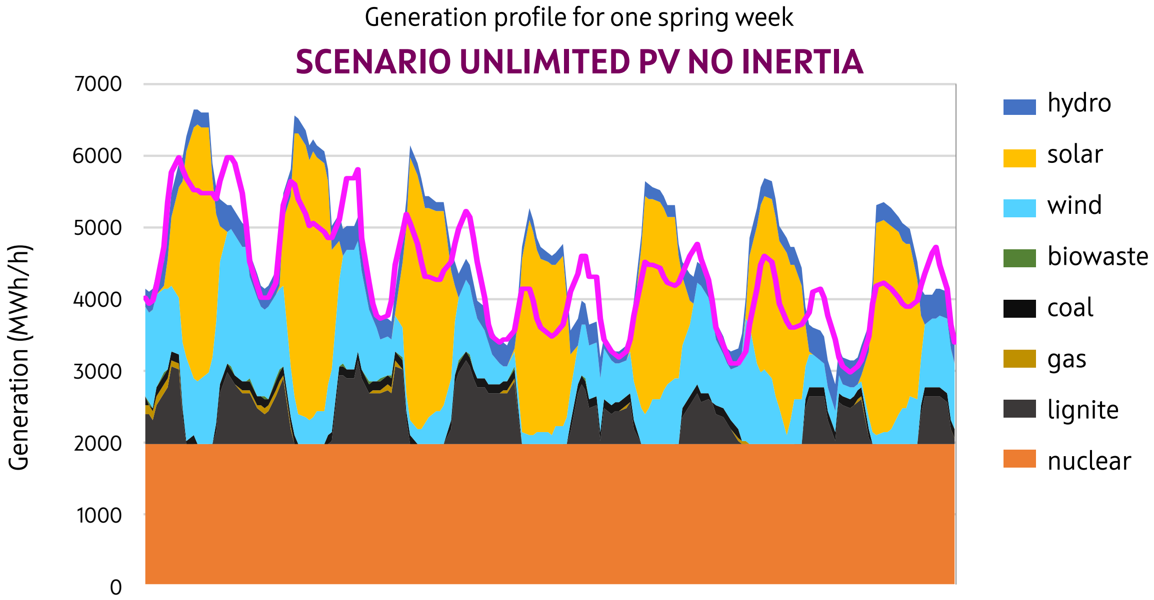
Wind energy plays a strong complementary role, contributing 25–30% of demand in at least 30 hours of the week (17% of the time), mainly during non-solar hours. On most days, wind covers 15–20% of nighttime demand, further reducing reliance on fossil fuels. Despite this, lignite and coal generation decrease compared to the base scenario, signaling a gradual shift away from fossil fuels. Hydropower continues to support system balancing, but thermal plants remain necessary due to inertia constraints.


Generation profile for one spring week

SCENARIO UNLIMITED PV

**FIGURE 8:** **FLEXTOOL MODELING RESULTS. GENERATION PROFILE FOR ONE SPRING WEEK IN THE UNLIMITED P SCENARIO**

In the scenario Unlimited PV, solar power plays a role similar to NECP 2030, further reducing fossil fuel generation. The system optimizes dispatch more effectively, leading to lower curtailment levels (below 5%) compared to NECP 2030. Wind generation remains stable, complementing solar, yet the reliance on nuclear and lignite persists due to the imposed inertia requirement. This scenario introduces greater flexibility in lignite usage, demonstrating that a more adaptable thermal generation fleet can support higher renewable integration.


Generation profile for one spring week

SCENARIO UNLIMITED PV NO INERTIA

**Figure 9:** **FLEXTOOL MODELING RESULTS. GENERATION PROFILE FOR ONE SPRING WEEK IN THE UNLIMITED PV SCENARIO (NO INERTIA CONSTRAINS)**

The removal of inertia constraints allows for the highest share of variable renewable energy integration, minimizing fossil fuel dependence. This scenario is the most theoretical one, as it assumes thermal power plants operate only 14 hours per day or just 60% of the time. PV generation surpasses 60% of demand for 5 to 9 hours per day, making storage and export capacity crucial to avoid excessive curtailment.

The absence of inertia constraints enables the system to absorb significantly more renewable energy, reducing curtailment and minimizing the need for lignite and coal plants to operate for grid stability. Wind power plays a larger role in complementing solar, leading to a more balanced and diversified generation mix that further reduces dependence on conventional power.

## 4.3.4. Inertia and Reserve

> Inertia values decline in all future scenarios compared to the base case (2025 status quo), reflecting the reduced presence of synchronous generators such as coal, nuclear, and gas plants, which traditionally provide system inertia.

The inertia analysis reveals the impact of increasing renewable energy penetration on grid stability. **Inertia values decline in all future scenarios compared to the base case (2025 status quo), reflecting the reduced presence of synchronous generators such as coal, nuclear, and gas plants, which traditionally provide system inertia.**

- **Base Scenario**: Inertia remains significantly higher throughout the year, as conventional generators continue to dominate the electricity mix, providing a steady source of system inertia.
- **NECP 2030**: A sharp reduction in inertia is observed due to the phase-out of part of the fossil fuel fleet and higher solar PV integration. **For almost 60% of the time the system operates at the critical threshold of 15 GWs, indicating potential grid stability challenges.**
- **Unlimited PV with Inertia Limits**: While this scenario also experiences lower inertia compared to the base case, the imposed inertia constraint ensures that conventional power plants remain online when necessary to maintain stability, which also ensures inertial level being higher than 15 GWs for 70 % of the time and the rest staying at the threshold level.
- **Unlimited PV with No Inertia Limits**: This scenario sees the most significant decline in inertia. **For nearly 5% of the year, inertia drops below 10 GWs**, a level that could severely challenge grid stability. The lack of inertia constraints allows more frequent displacement of conventional generators, leading to a reliance on alternative grid-stabilization measures.
- **The effect of VRE complementarity is well recognizable in the last scenario Unlim_VRE**, where inertial levels are above the threshold for half of the time and being stabilized at 15 GWs for the rest.

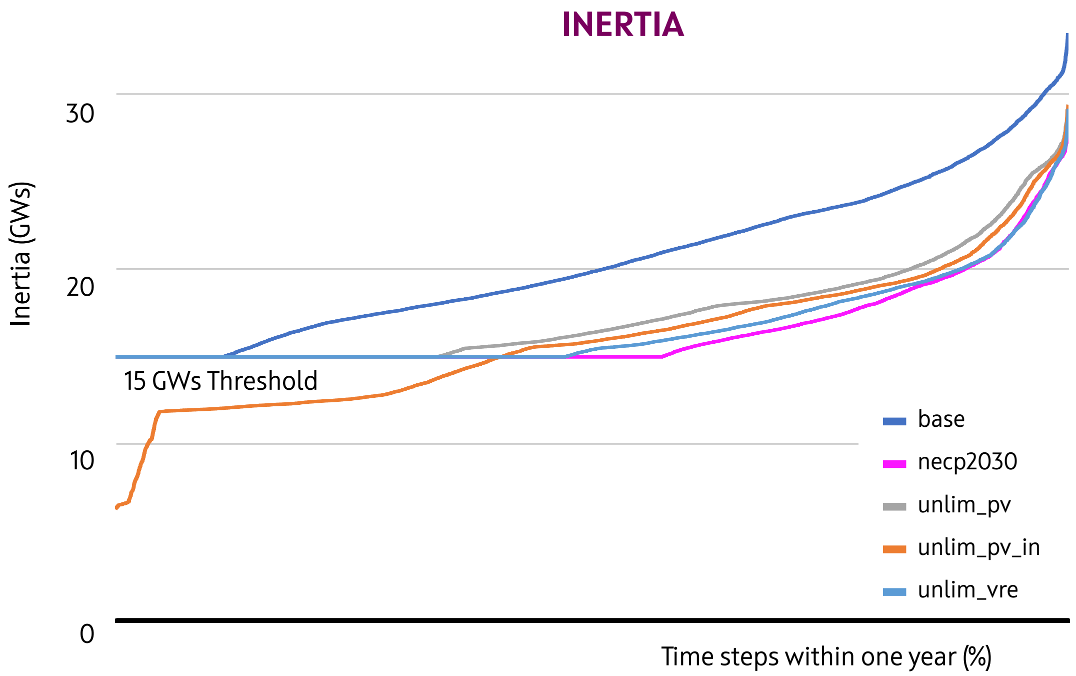


**FIGURE 10:** FLEXTOOL MODELING RESULTS. LEVELS OF INERTIA ACROSS SCENARIOS

## FCR Up Reserve Provision Across Scenarios

The Frequency Containment Reserve (FCR) analysis highlights the role of different generation sources in **providing immediate response to frequency deviations** in the system.

- **Base Scenario**: The majority of **FCR is provided by hydro and thermal power plants**, ensuring a stable grid response.
- **NECP 2030**: **The share of hydro increases, while thermal remains significant**, as fewer fossil fuel plants operate continuously, limiting their availability for reserves. **Variable renewables start to contribute minimally**, but their participation remains limited.
- **Unlimited PV with Inertia Limits**: Similar to NECP 2030, but with a **slight increase in hydro's share and a decline in thermal reserves**, reflecting the continued transition towards renewables.
- **Unlimited PV with No Inertia Limits**: **Pumped storage becomes the dominant source of FCR, while the contribution from hydro and thermal plants declines.** This shift indicates an increasing reliance on storage and flexible capacity to manage system stability as synchronous generation diminishes.

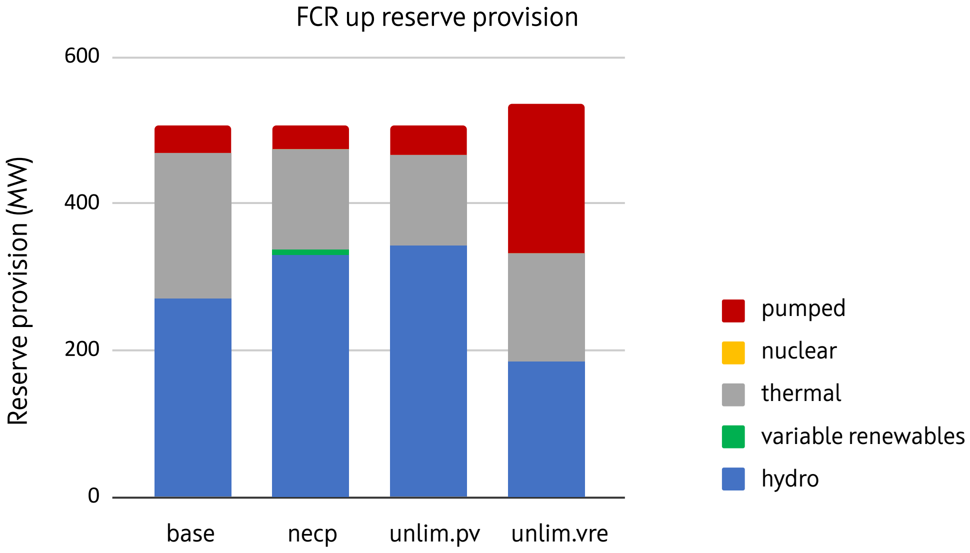


**Figure 11:** FLEXTOOL MODELING RESULTS. FREQUENCY CONTAINMENT RESERVE PROVISION ACROSS SCENARIOS

## 4.3.5. Total System Cost

The total annualized system costs for all 2030 scenarios range between 1.8 to 1.9 billion euros, reflecting the investment required to implement these energy transition pathways. These costs account for new generation capacity investments, storage deployment, fuel expenses, $CO_2$ costs, and fixed costs associated with maintaining the existing energy infrastructure.

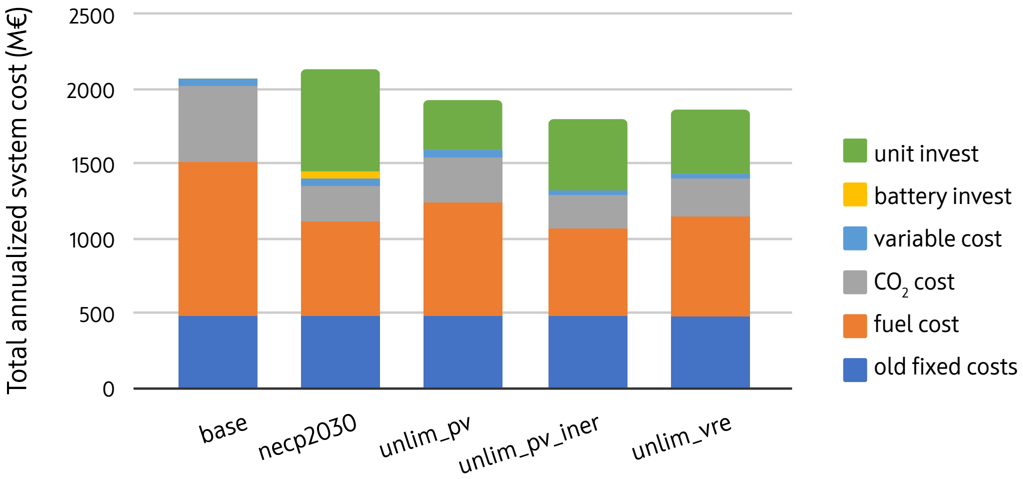


**FIGURE 12:** FLEXTOOL MODELING RESULTS. TOTAL ANNUALIZED SYSTEM COST

A key takeaway from the analysis is that scenarios dominated by VRE result in lower total system costs compared to the baseline (status quo) scenario. This cost reduction is primarily due to the displacement of fossil fuel consumption and the associated carbon costs, which are redirected toward financing new renewable energy investments. In contrast, maintaining the current system (base scenario) remains the most expensive pathway, as it relies on high fossil fuel expenditures and carbon pricing.

However, the NECP 2030 scenario, while achieving significant emissions reductions, presents the highest total system costs among the transition scenarios. This is mainly driven by large-scale PV investments, leading to overcapacity and increased capital expenditure. Although $CO_2$ costs decrease significantly in this scenario–more than in the PV Free scenario, where fossil fuel generation plays a more prominent role for system adequacy–the savings from reduced carbon costs are not enough to offset the high capital investments required for solar deployment.

Additionally, the scenarios allowing for a more balanced mix of VRE sources (wind and solar) tend to be more cost-effective, as they optimize resource complementarity, reduce curtailment, and limit unnecessary overinvestment in specific technologies.

# 5. CONCLUSION

The results of this analysis suggest a clear pathway for the transformation of the Bulgarian energy sector. This transformation necessitates a prominent role for VRE in achieving a future energy system that is green, reliable, and intelligent (smart). The analysis reveals a growing need for RES to provide a significant portion of the flexibility and ancillary services that will be required by the grid. To facilitate their optimal uptake into a smart grid, the following considerations are crucial:

- The increasing penetration of renewables, particularly solar, presents a challenge due to their inherent variability. During periods of high solar production, electricity prices may fall to zero or even turn negative, particularly on warm summer days. This price volatility can negatively impact the financial viability of renewable energy projects. Thus, the integration of RES with energy storage solutions is creating a new business model that benefits both grid operators and asset owners. This model facilitates grid balancing while enabling revenue generation for asset owners based on dynamic electricity prices. By enabling peak shaving, load shifting, and mitigating price volatility, energy storage paves the way for a more balanced and efficient energy market with increased RES penetration. Fluctuations in supply and demand will be minimized, leading to a more stable grid with fewer significant price swings. The best way in which this exchange of energy can be managed, is through the use of flexibility platforms and services.
- The inherent variability and uncertainty of VRE pose significant challenges for their system-level integration. To optimize grid operation and maintain stability, improved visibility and predictability of VRE generation are essential. Achieving this necessitates the development of a robust telecommunication infrastructure with low latency, high reliability and availability, and robust security standards.
- The energy sector is witnessing a significant shift in consumer behavior. Tradi-

tionally passive consumers are evolving into prosumers, actively participating in energy production and consumption. This trend is gaining momentum, with prosumers no longer a minority but rather a growing segment. Furthermore, the rise of smart homes and smart appliances is blurring the lines between consumption and production. These technologies enable real-time monitoring and control of energy usage, empowering consumers to become more proactive in managing their energy needs. The combination of prosumption, energy efficiency, and smart technologies has the potential to transform consumers into active participants in the energy market. Consumers could potentially provide flexibility services be it individually or through an aggregator.

- The role of power electronics is becoming increasingly critical in the transformation of the modern power grid. A key advancement in this field is the development of grid-forming inverters. These inverters offer substantial advantages for integrating RES and enhancing grid stability. Grid-Forming Inverters actively control and regulate both voltage and frequency. This capability allows them to mimic the behavior of conventional synchronous generators, which have historically served as the cornerstone of grid stability. The adoption of grid-forming inverters for RES offers several key benefits: enhanced RES integration, improved grid stability, increased grid flexibility and ability to self-regulate, as well as enabling a 100% RES grid.
- Electric vehicles present a double-edged sword for the energy grid. Their mass deployment will significantly increase electricity consumption, potentially straining grid capacity. However, EVs also offer exciting opportunities as distributed mobile storage units. They can be charged during off-peak hours or in areas with excess renewable energy. This stored energy can then be fed back into the grid during peak demand periods or locations through Vehicle-to-Grid technology. Moreover, EVs can be programmed for automatic charging and discharging based on market signals, optimizing grid stability and energy efficiency.

Effective management, planning, improved visibility, and advanced forecasting capabilities are the cornerstones of smart grids. These technologies empower the grid to become more self-regulating, preventing disruptions like blackouts, brownouts, load shedding, and the need to curtail renewable energy sources.

This analysis demonstrates that achieving a high penetration of variable renewable energy in the Bulgarian power grid is feasible, but only with the implementation of a robust flexibility strategy. The modeling highlights the critical role of a diversified renewable mix, where wind's higher capacity factors and its complementarity with solar help reduce inefficiencies and enhance overall system performance. To ensure grid stability and economic viability, adopting advanced technologies and flexibility measures is no longer optional–it is essential for a sustainable and resilient energy transition.

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