

Article

Sustainable Energy Transition Challenges: Limits to the Integration of Core Energy System Components—Reliability Perspective

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Abstract

The rapid expansion of non-dispatchable renewable energy sources (VRE) and energy storage technologies raises fundamental questions regarding the structural limits of their integration into power systems. This study aims to determine, from a structural reliability perspective, the adequate penetration limits of VRE in a synthetic power system and to assess how firm generation share, storage capacity, and wind–solar technology mix influence system reliability. A synthetic annual load profile reflecting current European conditions was developed from real-life data, along with a set of indicators enabling the consistent characterization and comparison of demand profiles. A deterministic system model was then applied to evaluate power and energy balance under parametrized configurations of firm generation, variable renewable capacity, and storage. Reliability performance was assessed using proposed indices (RIs) covering, among others, capacity margin, loss of load duration, frequency, etc. The results demonstrate the existence of structural penetration limits of non-dispatchable renewables that cannot be eliminated solely by increasing storage capacity, but only shifted. The technological composition of VRE is shown to be as important as total penetration: higher wind shares improve seasonal alignment and reduce reliability risks, whereas PV-dominated configurations increase curtailment and storage dependence. Moderate overcapacity, combined with a balanced wind–solar mix, provides the most favorable structural reliability conditions. These findings underscore the importance of incorporating reliability-based structural constraints into long-term energy transition planning, beyond purely economic optimization criteria.

Keywords: energy storage; renewable energy sources; energy systems; electricity production



Academic Editor: Fabio Maria Montagnino

Received: 30 January 2026

Revised: 20 February 2026

Accepted: 27 February 2026

Published: 1 March 2026

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1. Introduction

In recent years, the trend of energy transformation has been noticeable in many countries. The growing interest in renewable energy sources (RESs) is particularly noticeable, with their importance increasing year by year in many countries' energy mixes. In 2024, global electricity generation by RESs reached a record high of around 30.9 thousand TWh, which was 23% of the total final electricity consumption [1]. Renewable energy sources such as wind farms and photovoltaic installations play an important role in the decarbonization of the energy sector. About 116.8 GW of installed wind power capacity and 602 GW of solar photovoltaic (PV) capacity was added to the world's grids, which saw the global installed solar PV capacity grow by a record 37% between 2023 and 2024 [1]. The use of

renewable energy sources results in a reduction in greenhouse gas emissions, including carbon dioxide, during the electricity generation process. On the other hand, these sources are characterized by a variable amount of electricity produced, which depends largely on the prevailing weather conditions. From a legal framework, the energy from renewable energy sources has a priority in the network, as all generated energy is fed into the power system, irrespective of the current demand in the grid. This situation may require additional regulatory mechanisms that contribute to network stabilization. However, despite the significant increase in the importance of RESs, many countries in the world still base their electricity systems on fossil fuels such as coal or crude oil [2]. Hence, the process of decarbonization to achieve net-zero emissions, which is a state where, in a given area within the analyzed energy system, the sum of all greenhouse gases emitted into the atmosphere is balanced by their capture, removal, storage, or reuse in various industries and is a tedious and slow process, requiring long-term planning and forecasting. Designing an efficient energy system equipped with a high installation capacity for RES installations requires a stable core supplying the power grid with energy regardless of the prevailing weather conditions, energy storage units allowing for the use of surplus energy during an excess in the grid and storing it until a deficit occurs, and peak sources capable of quickly supplying electricity when a sudden demand occurs within the power system.

With the growing importance of renewable energy sources like PVs or wind farms (WFs) and their increased share in energy mixes, it is necessary to use additional methods of regulating the electricity grid by using energy storage technologies (ES), because a further increase in the installation capacity for renewable energy installations may inconveniently affect the stability of energy systems [3]. Currently, this task is mostly performed by pumped hydro storage power plants (PHS), which are well understood and commercially available energy storage technologies on a large scale [4]. PHS is a mature technology that currently represents around 96% of the global energy storage capacity [5]. Other possible technologies for storing large amounts of electricity within energy systems include compressed air energy storage systems (CAESs) and systems using hydrogen as an energy carrier [6,7]. Regardless of the choice of energy storage technology, these are expensive solutions, especially in terms of investment, but they are necessary when considering net-zero emission energy system scenarios.

The energy storage market is under rapid development; however, it has to be emphasized that it is currently focused on battery systems. Annual grid-scale battery storage additions, according to International Energy Agency data [8], are presented in Figure 1.

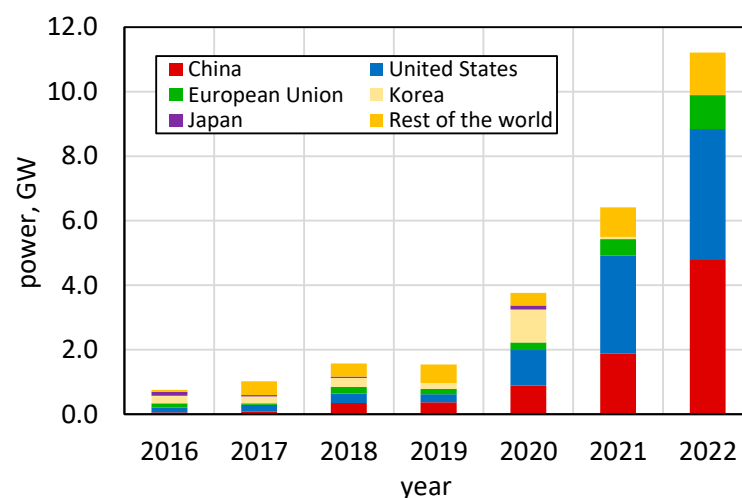


Figure 1. Annual grid-scale battery storage additions based on International Energy Agency data provided in [8].

This vast development is mostly in the USA and China. As presented in [9], California has 8179 MW of operating batteries, Texas has 4252 MW, Arizona has 858 MW, Nevada has 758 MW, and New York has 232 MW of battery systems. A flagship example of the effective use of battery systems is California, USA, whose generation mix consisted of almost 58% non-GHG and renewable sources [10], of which nuclear sources accounted for only 9.3%. In California, over 4 years, the grid-scale batteries' discharging power capabilities increased over 40 times, reaching over 8 GW at the end of 2024. However, European countries are also interested in increasing their grid flexibility potential, including the Netherlands (data for October 2024), which has 251 MW of running batteries and 176 MW of systems under construction. Permits for construction have been issued for another 1744 MW, with as many as 33 installations above 5 MW [11]. Utility-scale batteries are also becoming a reality in Europe, resulting in a noticeable reduction in capital expenditures—the United Kingdom, for example, boasts a 30% reduction in CAPEX in two years (from 2022) [12], even though 2022 was the first year since 2010 when a global increase in the price of lithium was observed due to the Russian invasion of Ukraine. Russia is the largest producer of grade 1 nickel for batteries, accounting for 20% of the global supply. It is also a top five producer of cobalt and graphite [13]. Given the cost and energy density, lithium iron phosphate (LFP) batteries are the preferred choice for grid-scale storage. Lithium-ion batteries with a higher energy density, such as nickel cobalt aluminum (NCA) and nickel manganese cobalt (NMC), are popular for energy storage located in households. Lithium supply thus remains one of the most critical elements shaping the future decarbonization of energy storage.

An important element of the design and management of energy systems are stable and failure-free sources ensuring a constant supply of electricity. In many cases, this core consists of installations using fossil fuels in the process of generating electricity. In 2024, the amount of electricity generated in units using fossil fuels was 59.1% globally [1]. Many energy systems, including Poland's, are largely based on the use of fossil fuels such as hard coal or lignite, where the installed power unit of this type is about 32 GW [14]. There is a similar situation in the countries of South-Eastern Europe, where power systems have high shares of electricity generation from coal-fired power units with quite a low efficiency [15]. Installations burning hydrocarbons in the process of generating electricity produce and emit significant amounts of greenhouse gases such as carbon dioxide into the atmosphere. In 2024, coal-fired power plants supplied about 55.9% of Poland's electricity.

Therefore, to significantly reduce pollutant emissions and achieve net-zero emissions while maintaining this type of installation in the power system, it is necessary to use CO₂ sequestration installations—Carbon Capture and Storage (CCS). Carbon Capture, Utilization and Storage (CCUS installations) aim at capturing carbon dioxide from industrial processes or fossil fuel-based power plants, with the idea to either store it permanently underground or utilize it through new chemistries. In the case of energy systems equipped with coal-fired power plants, these installations are also considered to play a crucial role in meeting the climate change and global warming reduction target [16].

In cases seeking to reduce greenhouse gas emissions from the energy sector without using additional costly sequestration installations, it is necessary to use other technological solutions that ensure the stable operation of energy systems. Nuclear power plants can provide such a solution [17]. Nuclear energy can be a crucial factor in the transformation to clean energy due to its ability to provide energy systems with secure, low carbon emissions during the electricity generation process and lower life cycle emissions than fossil fuels and some renewable energy sources, because studies have shown that the contribution of nuclear power to net carbon emission reduction should consider not only the relative carbon emission reductions from the replacement of coal power but also the carbon emissions of some or the whole life cycle [18,19]. Combined with the increasing deployment of RESs,

nuclear power plants can represent some of the key measures to achieving the net-zero carbon emissions target globally [20].

In energy systems where the base of the system is operated by units with limited or low regulation capabilities and a significant installed capacity of renewable energy sources—where the amount of electricity produced depends on the prevailing weather conditions—it is also necessary to use installations that guarantee the possibility of supplying additional power to the system when sudden peaks in demand occur. Gas turbine installations can play such role in the system, because they are characterized by a short response time and a high regulation range, which can be a response to the frequent occurrence of demand peaks in the power grid.

The description of energy systems using numerous defined indicators, in particular, the transformation path for these systems and the path to achieving net-zero emissions, is common in academic research. This topic was discussed in article [21], in which the author presents the results for the EROI (Energy Return on Investment) indicator defined as the ratio between the amount of usable energy produced by a power plant over its operational lifetime and the total amount of energy invested. The results of study show that, even with the EROI defined for highly developed systems, the maximum share of renewable energy sources may be significantly constrained. These results call for a reassessment of long-term plans for energy transition and the pursuit of net-zero emissions, in which renewable energy sources are to play a dominant role over synchronous generation capacities using nuclear or hydroelectric power, as well as power generated from the thermal conversion of fossil fuels, ensuring the stability and reliability of electricity supply within the energy system. The results presented by the author in article [21] suggest the need for a more honest discussion of the energy transition plan, which would allow for the implementation of realistic plans to achieve net-zero emissions for individual countries, taking into account their capabilities in this area and enabling long-term changes that would not affect the comfort of society and energy security.

Figure 2 summarizes the ranges of parameters analyzed in the literature on the integration of renewable energy sources (based on [22]). Colored areas represent the ranges of the VRE share in the total energy generation (horizontal axis) and the ratio of the energy storage capacity to the total energy demand (vertical axis) considered in the selected studies. The overview of these areas is the starting point for further analyses conducted in this paper.

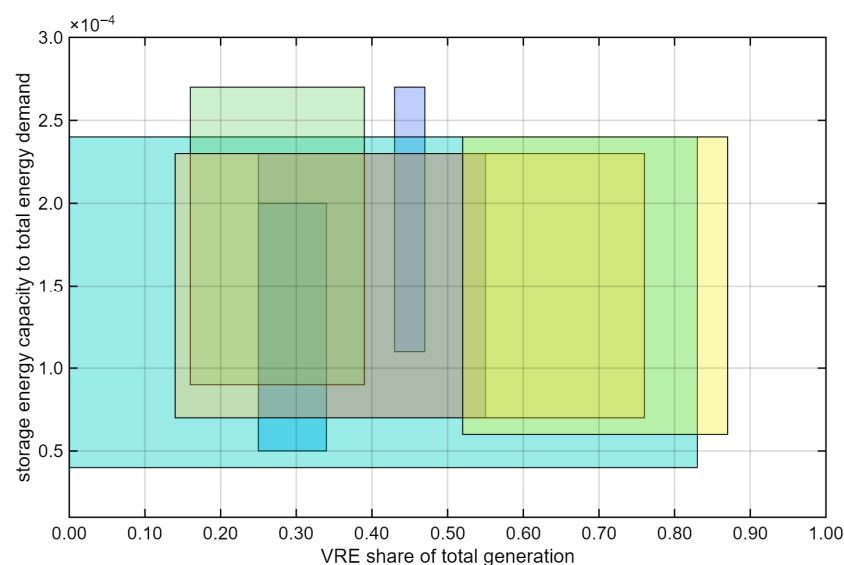


Figure 2. Areas of investigated relations between variable energy share in total generation of the energy system and storage energy capacity to total demand ratio based on data presented in [22].

Objective, Novelty, and Structure of the Paper

The main objective of this study is to determine, from a structural complementarity perspective and with a reliability impact, the effective penetration limits of non-dispatchable renewable energy sources in a synthetic energy system and to assess how key structural parameters, e.g., firm generation share, energy storage capacity, and the technological structure of variable renewable energy (wind vs. solar), influence system reliability.

The novelty of this study lies in a reliability-oriented assessment of high-penetration non-dispatchable renewable energy systems based on a synthetic yet representative European load profile. Instead of focusing on cost optimization, this paper introduces a coherent set of load profile indicators (SIs) and reliability indicators (RIs) to estimate the limits of VRE integration. Within this framework, the study addresses two central research questions: (1) Does increasing the energy storage capacity fully eliminate the effective penetration limit of non-dispatchable renewable sources? (2) How does the wind-to-solar generation ratio impact reliability indicators in high-VRE systems?

The results shown in the paper enable the identification of feasible operating regions for future low-emission power systems by jointly analyzing the roles of firm generation, flexible sources, and energy storage capacity. Importantly, the study demonstrates that increasing energy storage capacity shifts—but does not eliminate—the effective penetration limit of non-dispatchable renewables and that the technological structure of VRE (wind vs. solar) has a strong impact on system reliability.

The paper is organized as follows. Section 2 provides an overview of selected European energy systems, highlighting differences in energy mix structures and electricity demand trends. This overview motivated the development of a representative synthetic load profile. Section 3 describes the methodology applied in the study, including the construction and evaluation of the load profile, the formulation of the energy system model, and the definition of evaluation indices for both the system demand profile and system reliability. Section 4 provides an analysis of the results based on preselected case studies. Section 5 summarizes the findings and recommends areas worth exploring in future research.

2. Energy Systems in Selected European Countries

Several select energy systems of European countries with different characteristics of energy mixes were selected for further analysis. The authors analyzed the energy systems of Belgium, France, Italy, Poland, Sweden, and Switzerland (2000–2024). Table 1 presents the share of electricity generation sources for selected European countries, while Table 2 presents the share of total energy supply sources in those countries [23].

Analyzing the data presented in Tables 1 and 2, it can be seen that, both in terms of the sources responsible for electricity generation and in the case of total energy supply, the presented systems of the selected European countries differ from each other due to the resources used. In the case of fossil fuels used in the electricity production process in Europe, there are still countries that predominantly base their electricity systems on hard coal or lignite (Poland) or, to a large extent, on natural gas (Italy). In the case of countries with a low use of fossil fuels in the energy sector, it can be seen that their role is being taken over by nuclear energy, which is a key element of the electricity system in France, or the use of nuclear power plants combined with the increased production of electricity from renewable sources such as wind farms, photovoltaic installations, and hydropower, as is the case in Sweden and Switzerland. An interesting case is the Belgian power system, where one of the fossil fuels (natural gas), as well as nuclear energy and RESs are used to a large extent. In the case of total energy supply, fossil fuels such as hard coal, lignite, natural gas, oil, and their products still dominate in many countries. It is essential to take into account both electricity and heat generation sources when planning net-zero emissions energy

systems, which may be particularly important for European countries that, due to their geographical location and the associated climatic conditions, produce significant amounts of heat. Table 3 shows the total value and trend of electricity production in Belgium, France, Italy, Poland, Sweden, and Switzerland.

Table 1. The share of electricity generation sources in Belgium, France, Italy, Poland, Sweden, and Switzerland.

Country/Electricity Generation Source	Belgium	France	Italy	Poland	Sweden	Switzerland
Coal, %	2.90	0.36	1.71	55.90	0.20	0.00
Nuclear, %	41.30	66.80	0.00	0.00	29.30	29.20
Natural Gas, %	17.70	3.10	44.40	12.40	0.09	0.30
Oil, %	0.32	1.23	3.10	1.30	0.17	0.04
Wind, %	18.50	8.30	8.20	14.60	23.50	0.21
PV, %	10.60	4.10	13.20	9.00	2.40	7.20
Biofuels, %	3.10	1.37	5.40	4.40	4.10	1.18
Hydropower, %	2.14	13.60	19.80	1.85	37.70	59.40
Waste, %	3.15	0.78	1.76	0.004	2.52	2.48
Other, %	0.29	0.36	2.43	0.54	0.02	0.00

Table 2. The share of total energy supply sources in Belgium, France, Italy, Poland, Sweden, and Switzerland.

Country/Total Energy Supply	Belgium	France	Italy	Poland	Sweden	Switzerland
Coal and coal products, %	5.51	2.48	1.76	32.74	3.29	0.26
Natural gas, %	25.09	12.12	39.80	17.58	1.58	10.12
Hydropower, %	0.10	2.73	3.57	0.19	11.58	16.49
Nuclear, %	17.22	43.86	8.10	3.68	27.28	26.57
Solar wind and other renewables, %	4.05	3.03	11.16	12.91	9.72	2.47
Biofuels and waste, %	7.64	8.59	35.60	32.91	26.43	13.28
Oil and oil products, %	40.37	27.18	1.76	32.74	20.12	30.80

Table 3. Total value and trend of electricity production in Belgium, France, Italy, Poland, Sweden, and Switzerland.

	Belgium	France	Italy	Poland	Sweden	Switzerland
Total electricity production, GWh	75,677	569,511	273,294	169,355	172,091	82,183
Trend of electricity production (2000–2024), %	−10	+5	−1	+17	+18	+22

Based on available reports collected for European countries in [23], a general increase in total electricity production between 2000 and 2024 can be observed in most European countries (e.g., France, Poland, Sweden, and Switzerland). There are also power systems where this value did not change significantly in the analyzed years (e.g., Italy). The trend in total electricity production rarely becomes negative, which is related to a decrease in the amount of electricity produced between 2000 and 2024—Belgium is an example of such a power system. Globally, China is the world’s largest energy consumer and carbon emitter,

accounting for about one-third of global carbon emissions. Even for such a large economy, achieving net-zero emissions is a huge undertaking, requiring high costs and extensive analyses considering various scenario variances. China still has 35 years to achieve carbon neutrality, which poses a challenge for the country's electricity system, which is responsible for approximately 90% of its greenhouse gas emissions [24].

Due to the increasing demand for electricity in households in highly developed countries, it is important to take this trend into account when designing and modeling energy systems aiming for “net-zero”. Given differences in the structure of electricity networks across individual European countries, the demand for electricity, and the total energy supply, net-zero emissions planning requires an individual approach.

3. Methods

3.1. System Load Profile

The starting point for the analysis is a synthetic annual load profile of the energy system (presented in Figure 3), generated based on the analysis of the European countries' systems, which were described in the previous chapters of the article. The characteristics of the normalized load profile (in ordered form) in relation to the profiles of selected European energy systems are presented in Figure 4. The profile reflects typical daily and seasonal variations and can easily reflect the average system load type for a European country. In the presented studies, it was used as a starting point for the analysis of a synthetic energy system consisting of basic source elements: base generation, variable generation, energy storage, and peak generation.

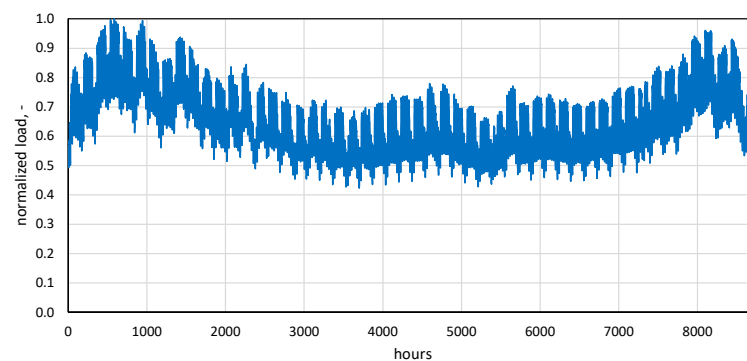


Figure 3. Normalized load profile as a function of time.

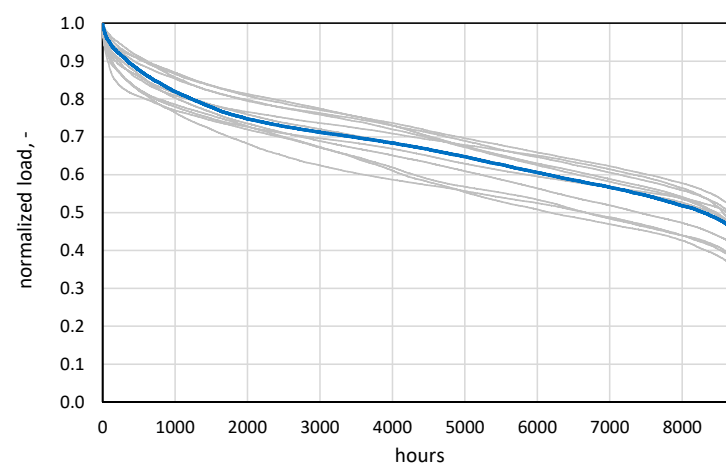


Figure 4. Normalized load profile in relation to the profiles of other real-life energy systems analyzed—ordered form. Blue line—synthetic profile, grey lines—selected European countries' profiles.

3.2. Load Profile Evaluation Indices

In order to analyze the generated energy system profile, a number of load profile variability indicators were introduced.

It should be noted that all of the compared load profiles are analyzed for the same time step to eliminate the impact of temporal resolution on the possibilities in order to compare the values of indicators for various profiles. It is very important for the analysis of results to take into account that the following analysis is performed for normalized values of the load profile. This is important for interpreting the results, e.g., for analyzing the range of the load profile (the equation is given in absolute values, but if it is applied to normalized values, the interpretation will differ, as emphasized in the description).

The SI_1 , described by Equation (1), also called the load factor, indicates how evenly distributed the load is in relation to the maximum value. If it is high, the profile is flat, with little difference between the valley and the peak. If it is low, the profile is variable, with large valleys and high peaks.

$$SI_1 = \frac{\text{avg}\{P_{load}\}}{\max\{P_{load}\}} \quad (1)$$

The second indicator, the peakiness index SI_2 (Equation (2)), is simply the inverse of SI_1 . It is logically redundant with respect to SI_1 , but the authors decided to show its values directly because they may be more intuitive for some researchers.

$$SI_2 = \frac{1}{SI_1} = \frac{\max\{P_{load}\}}{\text{avg}\{P_{load}\}} \quad (2)$$

The third indicator, SI_3 (Equation (3)), reflects the coefficient of variation and presents the variability relative to the average load level. A high value indicates relatively large fluctuations relative to the average; a low value indicates a stable, predictable profile.

$$SI_3 = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^n (P_{loadi} - \text{avg}\{P_{load}\})^2}}{\text{avg}\{P_{load}\}} \quad (3)$$

SI_4 , described by Equation (4), indicates the spread of the load profile. The formula was applied to normalized waveform values. High values indicate high variability, while low values indicate a nearly constant profile.

$$SI_4 = \max\{P_{load}\} - \min\{P_{load}\} \quad (4)$$

SI_5 (Equation (5)) refers to the change between steps, indicating the dynamics of the profile change. When applied to normalized values, it indicates the average load change between successive time steps, expressed as a fraction of the maximum annual power. Interpretatively, it is an indicator that shows how smooth or ragged the load profile is, on a scale from 0 to 1, where 1 represents a change equal to the entire power range. The higher the SI_5 , the more difficult it is to predict the profile, because the changes are rapid and frequent. For example, $SI_5 \approx 0.005$ means that in an average hour, the load changes by half a percent of the maximum annual load.

$$SI_5 = \frac{1}{n-1} \sum_{i=2}^n |P_{loadi} - P_{loadi-1}| \quad (5)$$

SI_6 , described by Equation (6), corresponds to the entropy (a measure of disorder). For normalized profiles, this indicates how diverse, complex, and multi-state the load profile is over time—the higher the SI_6 , the more variable, rich, and difficult to reduce to a simple pattern the load shape is.

$$SI_6 = -\sum_{i=1}^n \frac{P_{loadi}}{\sum_{j=1}^n P_{loadj}} \cdot \log_2 \left(\frac{P_{loadi}}{\sum_{j=1}^n P_{loadj}} \right) \quad (6)$$

SI_7 (Equation (7)) corresponds to the hourly load variability index and is a measure of average fluctuations between consecutive hours. It indicates how rapidly the load changes in percentage terms over time, i.e., how quickly the load changes, calculated as a percentage of where it currently stands. Comparing SI_5 (how much it changes, calculated in the range of 0–1) and SI_7 (how quickly it changes, calculated as a percentage of where it currently stands) presents different perspectives on the same time series.

$$SI_7 = \frac{1}{n-1} \sum_{i=1}^{n-1} \left| \frac{P_{loadi+1} - P_{loadi}}{P_{loadi}} \right| \quad (7)$$

3.3. General Description of the Energy System Model

The model used in the analysis is a balanced model of the power system based on the fundamental characteristics of individual sources. The model is deterministic in nature and uses historical or synthetic time series. Energy generation occurs in three primary sources: stable (firm) generation (e.g., nuclear and biomass sources in Polish conditions), flexible generation (gas peakers), and variable renewable sources (in this analysis, photovoltaics and onshore wind farms). An additional element of the balance is the energy storage system. The basic power balance met at each step of the simulation is represented by Equation (8):

$$P_{firmGen}(t) + P_{VRE_dir}(t) + P_{discharged}(t) + P_{flex}(t) + P_{unmet}(t) - P_{load}(t) = 0 \quad (8)$$

The power balance describing what happens with the variable renewable generation is represented by Equation (9). Renewable energy generated at time t is divided into power used directly, power used for charging the energy storage system, and power curtailed.

$$P_{VRE_dir}(t) + P_{VRE_char}(t) + P_{curt}(t) - P_{VRE}(t) = 0 \quad (9)$$

The energy storage system is modeled as an energy resource with a finite capacity, limited charging and discharging powers, and charging and discharging efficiencies resulting from the assumed round-trip efficiency (charging and discharging efficiency can be taken as the square root of round-trip efficiency, according to [25,26]). The energy balance of the storage system is presented in Equation (10):

$$SOC(t) + \eta_{ch} P_{VRE_char}(t) \Delta t - \frac{P_{discharged}(t) \Delta t}{\eta_{dis}} - SOC(t+1) = 0 \quad (10)$$

The sources allowed to charge the storage facility depend on the current balancing strategy. For this analysis, a strategy maximizing the use of VRE (through utilizing energy storage) was applied while maintaining the priority of the primary source, which is to achieve the maximum possible capacity factor. The general assumptions include:

- VRE production is predefined by an assumed time series and is uncontrollable;
- A stable source (e.g., nuclear) acts as the base source, operating at a predefined minimum level at least and has priority in the balance;
- Energy storage is used to balance the system using only (in the analyzed case) surpluses from VRE according to the fundamental concept of decarbonized systems;
- A flexible, dispatchable source is the last balancing element.

The strategy employed is not optimal in terms of cost or operation, but it aims to analyze the structural consequences of the assumptions made regarding the theoretical

basis of the operation of particular types of energy sources. In terms of input data on the unit efficiency of solar and onshore wind installations, data from [27,28] was used as the weighted average for NUTS2 (Nomenclature of Territorial Units for Statistics) units in a selected Central-Eastern European country, which corresponded to the nature of the modeled demand profile.

The purpose of the model is to quantitatively assess power and energy balancing at given structural parameters (installed capacity, capacity factor, storage capacity, and control strategies) and to determine the efficiency, reliability, and utilization indices for individual sources. The deterministic framework adopted in this study reflects a deliberate distinction between structural compatibility analysis and probabilistic adequacy assessment. The objective is not to evaluate operational reliability under stochastic variability but to identify feasibility regions resulting from defined relationships between firm generation, variable renewable penetration, storage capacity, and technology mix. Probabilistic adequacy modeling—typically incorporating forecast uncertainty, demand variability, forced outages, and extreme events—is designed to assess the reliability of a specific system configuration. In contrast, the present approach isolates intrinsic balancing constraints under controlled boundary conditions, focusing on interactions among core system components. This indicator-based analysis represents an essential first step in system planning by identifying parameter combinations (feasible regions) that are compatible or incompatible from a balancing (reliability) perspective.

3.4. Energy System Evaluation Indices

To evaluate the operational consistency of the theoretically analyzed system, several assessment indicators have been proposed. Some of them have been referred to as reliability indices, because together they provide a comprehensive picture of the potential risks associated with the excessive penetration of non-dispatchable sources in relation to dispatchable generation. Nevertheless, for a complete picture of the assessment, it is necessary to also take into account the other indicators presented. Indicators such as LOLP [14,29], although calculated in a recognized and very reliable manner, do not show the scale of the shortage. Although a discrete model was used, the following analysis attempts to show the scale of possible shortages and the areas of such power and capacity relationships of the individual system components for which we could consider the system to be capable of balancing.

The level of energy deficit compared to total energy demand can be defined as:

$$RI_1 = \frac{E_{def}}{E_{load}}, \quad (11)$$

where E_{def} , the amount of energy deficit, is defined by Equation (12),

$$E_{def} = E_{load} - E_{gen}, \quad (12)$$

E_{gen} is the total energy generated within the system, and E_{load} is the total energy demand.

The P_{gen} total generated power consists of variable renewable generation P_{VRE} , which combines solar and wind power (P_{PV} and P_{WF} , respectively), firm generation ($P_{firmGen}$), and flexible generation (P_{flex}), according to the following equation:

$$P_{gen} = P_{VRE} + P_{firmGen} + P_{flex} = P_{PV} + P_{WF} + P_{firmGen} + P_{flex} \quad (13)$$

P_{def} is the deficit power.

The expected duration of load loss, expressed in hours, is shown by

$$RI_2 = \sum_{t=1}^T 1_{\{P_{def}(t) > 0\}}, \quad (14)$$

Equations (15) and (16) allow us to evaluate the scale of the deficit power:

$$RI_{3,1} = \frac{\max\{P_{def}\}}{\max\{P_{load}\}}, \quad (15)$$

$$RI_{3,2} = \frac{\text{avg}\{P_{def}\}}{\max\{P_{load}\}}. \quad (16)$$

The capacity margin can be described as

$$RI_4 = \frac{P_{gen}^{nom} - \max\{P_{load}\}}{\max\{P_{load}\}}. \quad (17)$$

The deficits of power should be evaluated in terms of frequency and scale; therefore, the frequency in occurrence per year and scale expressed in hours per occurrence are defined according to Equations (18) and (19), respectively:

$$RI_5 = \sum_{t=2}^T 1_{\{P_{def}(t) > 0 \wedge P_{def}(t-1)=0\}}, \quad (18)$$

$$RI_6 = \frac{\sum_{t=1}^T 1_{\{P_{def}(t) > 0\}}}{\sum_{t=2}^T 1_{\{P_{def}(t) > 0 \wedge P_{def}(t-1)=0\}}}. \quad (19)$$

Additionally, the duration of the longest episode of the power shortage is defined as

$$RI_7 = \max_i \left(\sum_{t \in \text{epizod } i} \Delta t \right), \quad (20)$$

and the maximum deficit, as part of the total energy deficit, is calculated using the following equation:

$$RI_8 = \frac{\max_i \left(\sum_{t \in \text{epizod } i} P_{def}(t) \cdot \Delta t \right)}{E_{def}}. \quad (21)$$

The analysis performed in the presented paper was based on parametrized relationships between the elements of the energy system. To describe those relations, the following indices were used:

- Total variable power to peak load power ratio:

$$VTL = \frac{P_{VRE_total}}{P_{load_peak}}, \quad (22)$$

- Share of firm generation power in total installed power:

$$FSP = \frac{P_{firmGen}}{P_{gen}^{nom}}, \quad (23)$$

- Share of wind-generated energy in total variable energy:

$$WS = \frac{E_{WF}}{E_{VRE_total}}, \quad (24)$$

- Share of energy from firm generation in total load:

$$FSL = \frac{E_{firmGen}}{E_{load}}, \quad (25)$$

- Nominal energy storage capacity to total energy demand ratio:

$$ESSL = \frac{E_{storage_nom}}{E_{load}}, \quad (26)$$

- Variable renewable energy utilization factor:

$$VUF = \frac{E_{VRE_cons}}{E_{VRE_total}}, \quad (27)$$

- Flexible generation utilization factor:

$$FGUF = \frac{E_{flex}}{P_{flex}^{nom} \cdot 8760}, \quad (28)$$

- Energy storage utilization factor, defined as a ration of the discharged energy to the maximum possible discharge, assuming a daily operation cycle:

$$SUF = \frac{E_{discharged}}{days \cdot E_{storage_nom} \cdot \eta_{RTE}}, \quad (29)$$

4. Results

4.1. Load Profile Evaluation

The analysis compared the load profiles of the energy systems of several selected European countries using a set of defined indicators, SI_1 – SI_7 , calculated on the basis of normalized data (0–1). Normalization allows for only the shape of the profile to be assessed, regardless of the size of the system and the actual load capacity. Data for the aggregated European Union is not the subject of a detailed analysis; however, the authors decided to present it for big-picture awareness. Figure 5 shows the values of the SI_1 – SI_7 indicators for the selected energy systems of European countries and synthetic load profiles used for calculations in this paper.

Based on the first two indicators, it can be concluded that the most stable profiles among the group analyzed were observed in Belgium ($SI_1 = 0.724$), Poland ($SI_1 = 0.700$), and Switzerland ($SI_1 = 0.696$). In these countries, the differences between average and peak loads are relatively small. The profiles are more “baseload” in nature, and the systems are more predictable than others and relatively evenly loaded throughout the year. The peakiest profiles are found in France ($SI_1 = 0.595$), Italy ($SI_1 = 0.599$), and Sweden ($SI_1 = 0.613$). These systems are characterized by more pronounced differences between minimum and maximum load values, indicating greater seasonal or daily variability.

The SI_3 indicator shows that low relative variability is characteristic of the profiles of Belgium ($SI_3 = 0.150$) and Switzerland ($SI_3 = 0.140$)—changes are more predictable and milder. In these systems, the load is subject to smaller deviations from the average than in other cases. Italy and Sweden have more dynamic fluctuations in relation to the typical load level. These countries also have the highest load amplitude (Italy $SI_4 = 0.687$, Sweden $SI_4 = 0.661$).

France, Belgium, and Poland have the mildest profiles with the lowest average load variation in the real-life profiles. Italy and Switzerland are among the most dynamic. Sweden is an interesting case here, characterized by high seasonality but lower dynamics in the short term (high profile range—high value of SI_4 , but low values of indicators responsible for dynamics $SI_5 = 0.015$ and $SI_7 = 0.025$). Entropy (SI_6) is at a similar level for all countries, which suggests that the profiles are characterized by a similar complexity and the range of load states is similar.

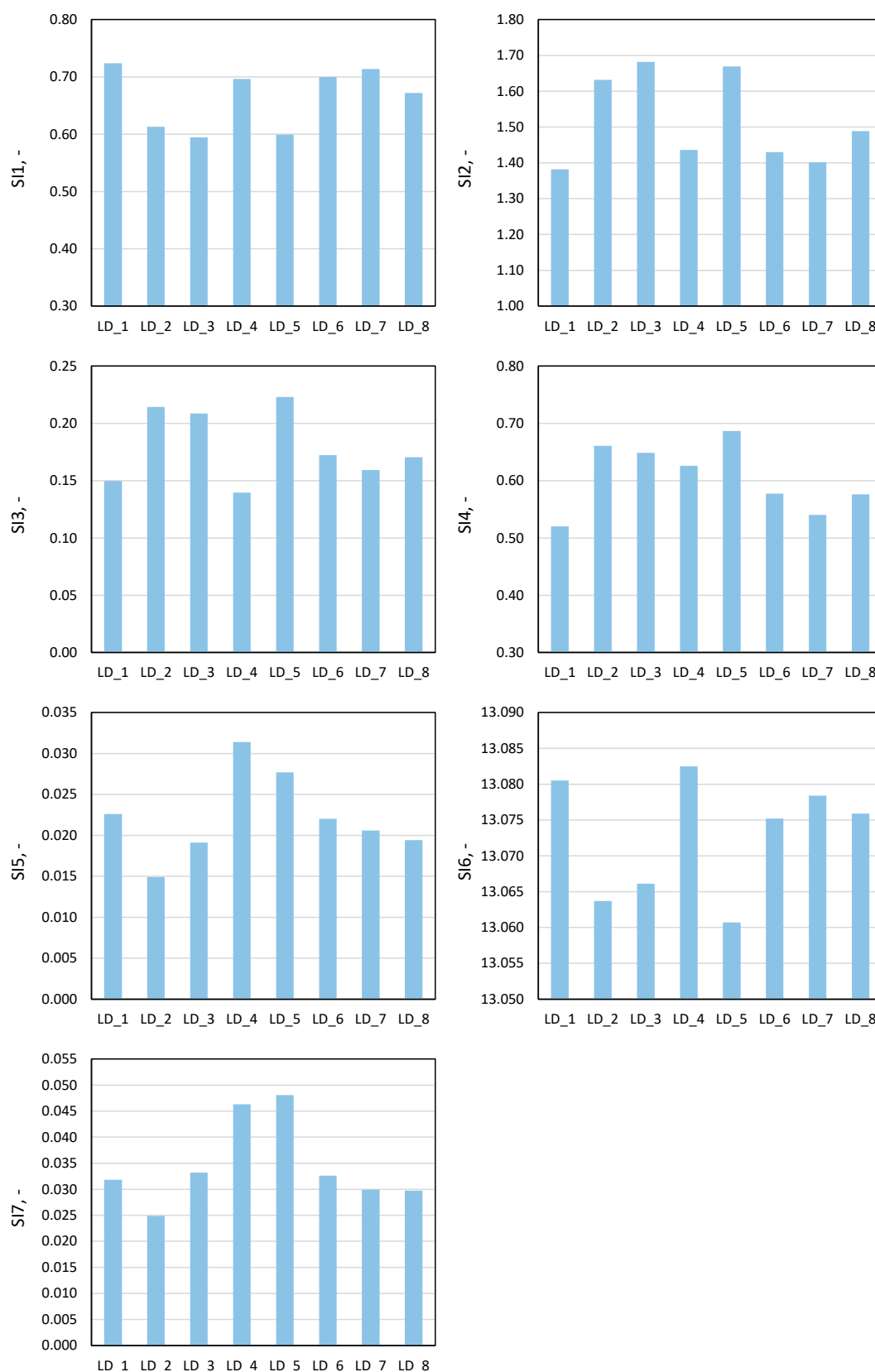


Figure 5. The values of the SI_1 – SI_7 indicators for selected energy systems of European countries and synthetic load profile, where LD_1—Belgium; LD_2—Sweden; LD_3—France; LD_4—Switzerland; LD_5—Italy; LD_6—Poland; LD_7—European Union; and LD_8—synthetic load profiles used for calculations in this study.

On this basis, the generated synthetic profile can be assessed as a profile with a relatively smooth course, moderate dynamics, and entropy similar to real countries. It can definitely be used to analyze simulated energy systems, as it reflects well the general characteristics of European systems.

4.2. Energy System Evaluation

The analysis focused on assessing the parameters of prospective energy systems, concentrating on the impact of the growing share of non-dispatchable sources and the scale of the necessary share of firm generation. The assessment was carried out using the RIs and auxiliary indicators described in Section 3.3. All results presented in this subsection were obtained for a synthetic load profile representative of average European conditions. In the analyzed case, it was assumed that the maximum load power is 33 GW, which translates into roughly 194 TWh of electricity demand per year. The installed capacity of the flexible source (gas peakers) is constant and assumed to be 11 GW.

Figure 6 shows the potential use of stable sources (firm generation) in the range of 0.3 to 0.5 of the total demand, which translates into installations with an installed power capacity of approximately 6.65 GW to 11.083 GW. Depending on the scale of the installed capacity in non-dispatchable sources (VTL), the share of firm sources in the total installed capacity (FSP) ranges from 0.0797 to 0.1258 (for $VTL = 2$) and 0.0492 to 0.0806 (for $VTL = 3.5$).

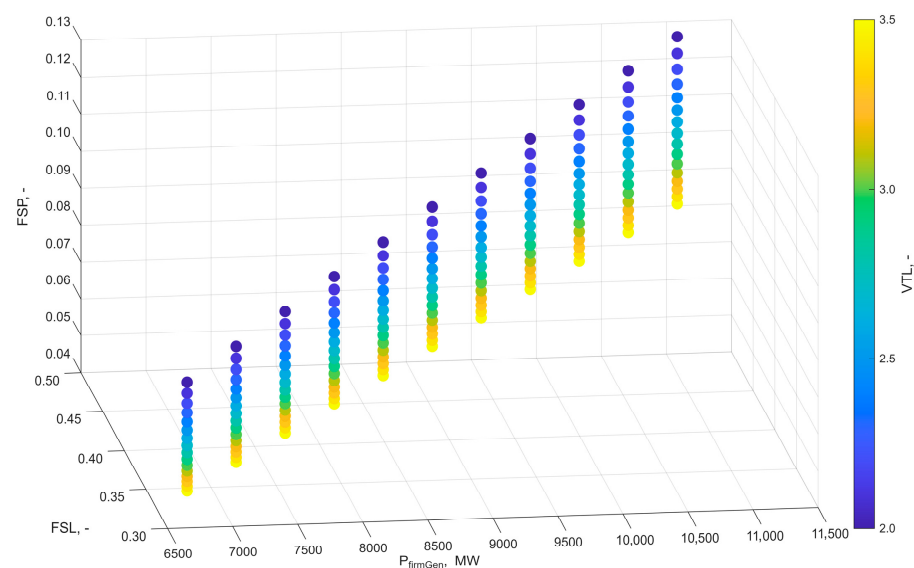


Figure 6. Firm generation power capacity potential.

For the purpose of further analysis of the reliability indicators, the $FSL = 0.5$ system was selected. Figure 7 shows the RI indicators for a fairly limited energy storage capacity in the system ($ESSL = 0.0001$), which translates into a power capacity of approximately 2.43 GW and an energy capacity of 19.4 GWh. These parameters correspond to the ability to compensate for only a small part of daily demand fluctuations. Figure 8 shows the VUF , $FGUF$, and SUF indicators for the same system. It should be noted here that in the target net-zero system scenarios analyzed in the literature, the VTL value quickly reaches a level above 3. The significant impact of wind power generation on unavailable sources is also clearly evident, with its dominant nature having a positive effect on reliability indicators (primarily, a higher capacity factor ensures the energy balance of the system) but also reducing the maximum ($RI_{3,1}$) and average ($RI_{3,2}$) capacity deficits.

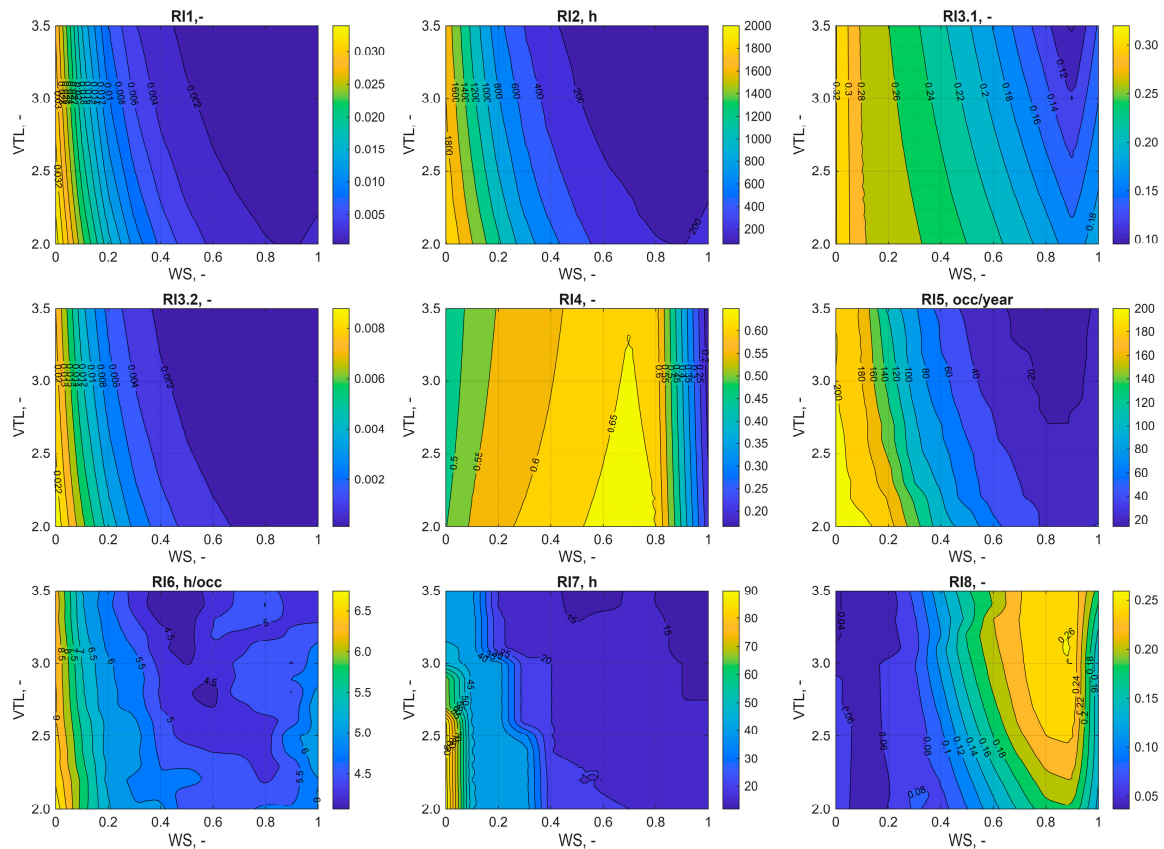


Figure 7. The values of the reliability indices for the analyzed system (ESSL = 0.0001).

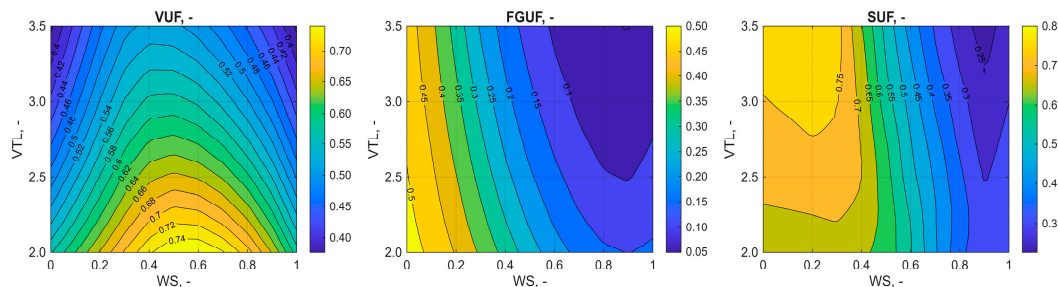


Figure 8. The values of the VUF, FGUF, and SUF indices for the analyzed system (ESSL = 0.0001).

In the case of the average capacity deficit, the wind share above approximately 0.65 reaches values below 66 MW, which suggests that this could be balanced with little effort, but thanks to $RI_{3,1}$, it can be seen that the maximum reaches several gigawatts, which is why the system would not be able to balance itself without imports from outside the country. Regardless of this, even the system with the highest installed capacity among those analyzed has a highly unsatisfactory RI_2 index value, reaching nearly 200 h of imbalance per year.

The number of deficits (RI_5) also strongly depends on the generation structure in uncontrollable sources, and once again, the dominant share of wind sources is highlighted. However, if we look at RI_6 , which determines the average length of the deficit (in hours), it turns out that oversizing the wind share will not bring benefits, and balance is necessary.

When it comes to the longest episode of energy deficit (RI_7), the dominance of solar sources is highly disadvantageous. RI_8 again confirms, from the point of view of energy shortages, that there is an optimal share of wind generation (of course, the point will vary slightly depending on the climate of the year analyzed, demand profile, etc., but the range

of 0.65–0.75 for the analyzed data seems to be a good choice). This is also the area with the largest capacity margin (RI_4).

Figure 8 shows that, with an adequate installed capacity in non-dispatchable sources, the lowest use of flexible generation sources ($FGUF$) was achieved for this range, even below 10%. In this range, the use of non-dispatchable sources can also be maximized—the VUF indicator shows a strong tendency toward the optimum here. However, high VTL values will require high curtailment. Maximizing the share of solar sources increases the degree of energy storage utilization (SUF), which indicates a better match between the wind generation profile and the demand profile and an increase in the share of energy used directly.

Figure 9 shows contour maps of system utilization indicators for a scenario with a moderate energy storage capacity ($ESSL = 0.001$, corresponding to the storage energy capacity of 194 GWh and power capacity of 24.3 GW): variable generation utilization factor (VUF), flexible generation utilization factor ($FGUF$), and energy storage utilization factor (SUF), as a function of the VTL , and the share of wind energy in total VRE generation (WS).

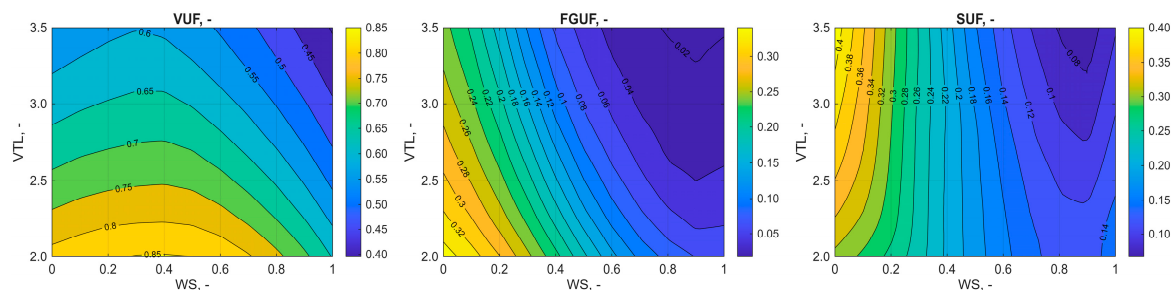


Figure 9. The values of the VUF , $FGUF$, and SUF indices for the analyzed system ($ESSL = 0.001$).

The VUF indicator reaches its highest values for moderate VTL values (≈ 2.0 – 2.6) and low and medium wind energy share ($WS \approx 0.2$ – 0.5). This means that, within this range of parameters, the system is able to effectively integrate energy from VRE, using both direct consumption and energy storage. As VTL increases, a systematic decrease in VUF is observed, especially for high WS values, indicating a growing problem of energy surpluses and generation reduction with high VRE penetration. This phenomenon indicates that the system's absorption capacity limit is being reached. The maximum utilization of renewable sources, together with a significant increase in storage capacity, has shifted towards a greater share of solar sources, which is due to the greater possibility of indirect (through storage) consumption of RES, as confirmed by the SUF indicator, which reaches its highest values for low wind share ($WS < 0.3$) and high VTL values. This means that intensive use of energy storage in systems is dominated by photovoltaics, where there are clear energy surpluses during daylight hours. As WS increases, SUF decreases, indicating a lower load on storage in systems with a higher share of wind energy.

The $FGUF$ indicator decreases with an increase in WS and a decrease in VTL , which confirms that a higher share of wind energy and a moderate level of VRE are conducive to reducing the use of flexible fossil fuel-based sources. The lowest $FGUF$ values occur in areas with high WS and moderate and high VTL , which indicates the most favorable operating conditions for the system in terms of reducing the demand for flexible (gas) generation. However, at very high VTL values, even a high share of wind does not completely eliminate the need to activate flexible sources, which confirms the existence of structural limitations in system balancing.

The analysis of the presented results indicates the existence of an optimal operating range for the system at moderate VTL values and a balanced VRE structure in which the use of renewable energy is maximized, the use of flexible sources is minimized, and

energy storage is used efficiently. Outside this area, further increases in the VRE capacity led to diminishing system benefits, confirming that, even at $ESSL = 0.001$, the energy storage shifts but does not eliminate the effective penetration limit of non-dispatchable renewable sources.

The results of this study are consistent with broader theoretical discussions on the limits of renewable integration and system adequacy in high-VRE systems, e.g., [14,22,29]. In line with previous research emphasizing the balancing of constraints and structural complementarity, the analysis confirms that increasing renewable penetration not only requires additional capacity but also an appropriate technological composition and coordination with firm generation and storage resources.

5. Conclusions and Recommendations for Future Work

The research presented in the paper can be concluded as follows:

- A synthetic load profile representative of average European conditions was developed and validated using a set of system load indices (SI_1 – SI_7), ensuring comparability with real national power systems.
- The proposed reliability indicators (RI_1 – RI_8) not only allow for the identification of loss-of-load events but also their scale, duration, reference to the capacity margin, and scale of intervention needed, providing deeper insight than traditional metrics.
- Results confirm the existence of an effective penetration limit of non-dispatchable renewable energy sources, which cannot be fully eliminated by increasing the energy storage capacity (increasing energy storage capacity only shifts the limits).
- The technological structure of VRE is shown to be as important as its total penetration level: higher shares of wind energy improve reliability due to better seasonal alignment with demand, while PV-dominated systems show higher curtailment and storage utilization.
- Moderate levels of VRE overcapacity combined with a balanced wind–solar mix led to the best system performance, maximizing renewable utilization while minimizing reliance on flexible fossil-based generation.

From a policy and planning perspective, the results show that storage expansion cannot be treated as the only solution to increasing VRE penetration. A reasonable mix of the system's fundamental components is crucial for defining decarbonization pathways. These findings highlight the necessity of including reliability-based constraints in long-term energy transition planning, beyond cost and emission criteria alone.

In further research, it is recommended to extend the presented analysis to include the impact of extreme climate events, which can significantly affect the reliability of power systems with a high share of non-dispatchable renewable sources, especially in operating regions identified in this study as being close to the effective penetration limits of VRE (it should be noted that those are operating regions proposed in most studies trying to reach climate neutrality). Another important direction for the development of the proposed model is the use of a probabilistic approach (e.g., [29]) that allows for the uncertainty of VRE generation forecasts, demand, and the availability of generation units to be taken into account, which would enable a more realistic assessment of the risk of power and energy shortages. In addition, future research should include the integration of economic criteria, such as capital investment costs and operating costs, with the assessment of system reliability in order to identify trade-offs between energy security and cost-effectiveness.

Author Contributions: Conceptualization, W.U. and M.J.; Data curation, M.J. and L.R.; Formal analysis, M.J.; Funding acquisition, W.U.; Investigation, W.U., M.J. and J.O.; Methodology, W.U.; Project administration, W.U.; Resources, J.O. and L.R.; Software, W.U.; Supervision, W.U.; Visualization, W.U. and L.R.; Writing—original draft, W.U. and M.J.; Writing—review and editing, W.U. and M.J. All authors have read and agreed to the published version of the manuscript.

Funding: The research presented in the work was carried out within statutory research funds for young scientists of the Silesian University of Technology, grant number BKM-595/RIE5/2025 (08/050/BKM_25/0390).

Data Availability Statement: The original contributions presented in this study are included in this article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations, symbols or subscripts used in this manuscript are detailed below:

CAES	Compressed Air Energy Storage Systems
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization and Storage
CM	Capacity Margin
EROI	Energy Return on Investment
ES	Energy Storage
ESSL	Storage Nominal Energy Capacity to Total Energy Demand Ratio
FGUF	Flexible Generation Utilization Factor
FSL	Share of Energy From Firm Generation in Total Load
GHG	Greenhouse Gases
LFP	Lithium Iron Phosphate Battery
LOLP	Loss of Load Probability
NCA	Nickel-Cobalt-Aluminum
NMC	Nickel-Manganese-Cobalt
PHS	Pumped Hydro Storage Power Plants
PV	Photovoltaics
RES	Renewable Energy Sources
SUF	Energy Storage Utilization Factor
VTL	Total Variable Power to Peak Load Power Ratio
VUF	Variable Renewable Energy Utilization Factor
WF	Wind Farm
WS	Share of Wind-Generated Energy in Total Variable Energy

Symbols

SI_{1-7}	System Load Evaluation Indices
RI_{1-8}	Power System Reliability Indices

Subscript

curt	Curtailment
def	Deficit
discharged	Discharged from Storage
firmGen	Firm Generation
flex	Flexible Generation
load	Load/Demand Value
nom	Nominal Unmet
VRE	Variable Renewable Generation
VRE_char	Storage Charging from VRE Source
VRE_dir	Flexible Generation

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