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Functional Model of Power Grid Stabilization in the Green Hydrogen Supply Chain System—Conceptual Assumptions

Marzena Frankowska *, Andrzej Rzeczycki, Mariusz Sowa and Wojciech Drożdż

Management Institute, University of Szczecin, 70-453 Szczecin, Poland
* Correspondence: marzena.frankowska@usz.edu.pl

Abstract: Green hydrogen supply chain includes supply sources, production, and distribution of hydrogen produced from renewable energy sources (RES). It is a promising scientific and application area, as it is related to the problem of instability of power grids supplied with RES. The article presents the conceptual assumptions of the research on the design of a functional multi-criteria model of the stabilization model architecture of energy distribution networks based on a hydrogen energy buffer, taking into account the applicable use of hydrogen. The aim of the research was to identify the variables contributing to the stabilization of the operation of distribution networks. The method used to obtain this result was a systematic review of the literature using the technique of in-depth analysis of full-text articles and expert consultations. The concept of a functional model was described as a matrix in two dimensions in which the identified variables were embedded. The first dimension covers the phases of the supply chain: procurement and production along with storage and distribution. The second dimension divides the separate factors into technical, economic, and logistic. The research was conducted in the context of system optimization from the point of view of the operator of the energy distribution system. As a result of the research, several benefits resulting from stabilization using a hydrogen buffer were identified. Furthermore, the model may be used in designing solutions stabilizing the operation of power grids in which there are surpluses of electricity produced from RES. Due to the applied multidimensional approach, the developed model is recommended for use, as it enables the design of solutions in a systemic manner. Due to the growing level of energy obtained from renewable energy sources, the issue of stabilizing the energy network is becoming increasingly important for energy network distributors.

Keywords: hydrogen supply chains; electricity networks; stabilization model; renewable energy sources; green hydrogen

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1. Introduction

The issue of the development of hydrogen technologies has its reference in the activities widely undertaken in many countries to develop hydrogen policies as integral parts of energy and climate policies. They are a response to the changes taking place in the European and global energy landscape and are related to the observed technological race in the field of innovative methods of production, transport and use of hydrogen. These efforts are accompanied by the emergence of numerous national and regional policies and strategies. The driving force behind these processes are changes in energy policy stimulated by the climate policy goals, aimed at moving away from conventional fuels in favor of zero- and low-emission solutions (decarbonization).

Hydrogen plays an increasingly important role in the European Union's decarbonization policy as one of the key energy carriers. According to the "Green Deal" strategy, investments in electrolyzers by 2030 may amount to between EUR 24 and 42 billion. At the same time, the increase in supply from solar and wind power connected to electrolyzers is estimated at 80–120 GW. The cost of these investments is in the range of EUR 220–340 billion.

In addition, there are the costs of investment in the distribution and transport infrastructure of hydrogen as a fuel, which is estimated at EUR 65 billion. Upgrading half of the existing power plants with carbon capture and storage equipment costs approximately EUR 11 billion [1].

On the other hand, in response to the hardships and global energy market disruption caused by Russia's invasion of Ukraine, the European Commission has presented the REPowerEU Plan, which consists of financial and legal measures. One of the main components of REPowerEU is an action titled "producing clean energy", aiming to fast forward the green transition while increasing the resilience of the EU-wide energy system. Thus, the Commission is proposing to increase the EU's 2030 target for renewables from the current 40% to 45% and to develop innovative technologies for the hydrogen value chain to decarbonize industrial processes and mobility [2].

There is a need to fill the research gap concerning the functioning of the hydrogen supply chain (HSC), with particular emphasis on the first phase of the chain, which is the supply of raw materials from renewable energy sources along with storage. Previous research has focused mainly on technical and economic factors. It has not taken into account social, regulatory, and political factors. Moreover, it also does not include the estimation of the risk related to weather conditions, energy costs, and the size of the demand [3,4]. Supply chain models for hydrogen obtained through electrolysis require a storage phase, which is a source of meeting the demand for hydrogen fuel obtained from renewable energy sources. The subject of HSC modeling in the scope of the storage phase is widely covered in current research in the world.

Modern hydrogen technologies are used mainly in energy and transport and support the pursuit of climate neutrality in other sectors of the economy. In the literature, there are various nomenclatures used depending on the raw material or energy source used for the production of hydrogen. This is the reason that hydrogen generation technologies are often classified based on different colors, e.g., grey, blue, turquoise, green, purple, and yellow [5]. Gray hydrogen is created from natural gas, or methane, using steam methane reformation but without capturing the greenhouse gases made in the process. Green hydrogen is generated by RES produced in the electrolysis process. This kind of hydrogen is of special interest in transitioning toward a more sustainable energy and transport system. In the literature, there are also synonyms for terms such as "clean hydrogen", "renewable hydrogen", or "low-carbon hydrogen". However, it should be pointed out that green hydrogen is not yet sufficiently cost-competitive as compared to gray hydrogen. In order to exploit all opportunities related to hydrogen, the European Union is implementing a strategic approach to achieving climate neutrality by 2050 [5]. This approach combines various areas of action covering the entire value chain, including industrial, market, and infrastructure aspects, taking into account the perspective of technological development and innovation as well as the international dimension, by planning to create conditions enabling an increase in the supply and demand for hydrogen. Moreover, it identifies "clean hydrogen" and its value chain as one of the key areas for unlocking investment to support sustainable economic development and employment. These actions are also important in the context of recovery from the crisis related to the COVID-19 pandemic [6].

At the same time, the climate policy pursued by the EU assumes an increase in the volume of electricity generated from renewable energy sources. Increasing the share of electricity generated from renewable energy sources (RES) in the energy balance is a great challenge for most developed economies in the world. The systematic increase in the share of photovoltaics, wind energy, and other renewable energy sources in the energy mix of EU countries implies problems related to balancing supply and demand in the energy market. Due to the lack of adequately advanced technologies for large-scale energy storage and services for balancing power systems, the development of renewable energy sources is difficult. Hydrogen obtained from electrolysis may play an important role in storing energy generated from renewable energy sources and thus participate in increasing the possibilities of integrating and stabilizing energy from renewable sources in the energy system.

However, introducing hydrogen applications in Europe poses significant challenges that neither the private sector nor the member states can tackle on their own. Regulatory gaps, which constitute a barrier to the development of the application of hydrogen technologies, are observed. A breakthrough in the development of hydrogen technologies requires the so-called critical mass of investment, a favorable regulatory framework, but also new lead markets, in-depth research, and technological innovation. Furthermore, it also requires a large-scale infrastructure network. In order to build a dynamic hydrogen ecosystem in Europe, it is necessary for all actors, both public and private, at European, national, and regional levels, to work together across the entire value chain [7].

More and more intense activities of individual European Union countries focusing on creating optimal conditions for the development of the hydrogen economy can be noticed. These activities serve to remove institutional barriers and at the same time create formal and legal conditions in which the economy would become more innovative and competitive. Removing formal and legal barriers is also one of the main political and regulatory challenges. The growing importance of the hydrogen market, with simultaneous legal loopholes for hydrogen as an alternative fuel, shows the importance of the problem and its importance for the development of hydrogen technologies, especially in the field of energy transformation and electricity storage.

The article fills the identified research gap and meets the urgent need for a comprehensive approach to the discussed issues from the point of view of the operator of the energy distribution system. The work presents the assumptions of the functional model describing the dependencies related to the development of an intelligent and maintenance-free system for stabilizing the operation of electricity distribution networks based on modular installations of a hydrogen energy buffer with the perspective of the applicable use of hydrogen. The model should include four utility functions [8]:

- Conversion of electricity to hydrogen;
- Fuel cell that converts hydrogen into electricity;
- Hydrogen storage;
- Utility use of hydrogen.

An innovative approach is an attempt to develop coefficients that create a functional model for stabilizing the operation of distribution networks, which takes into account the utility described in the paper. These factors relate to the three main phases of the hydrogen supply chain. System stabilization should be understood as balancing the supply and demand for electricity transferred to the receiver performing work or changing it to another form of energy, taking into account transmission losses. The research results presented in the paper show that the developed model of stabilization of the energy distribution network allows for productive (efficient) management of electricity. In addition, it will allow increasing the flexibility of the network in the area of connecting new energy producers from renewable energy sources (RES) as well as increasing the level of safety and use of the network under certain conditions while maintaining the ability to meet the requirements within a specific period of use. The test results prove that the quality parameters of the electricity supplied to consumers will improve.

2. Materials and Methods

The basis of the research process was a systematic literature review (SLR). In the process of systematic literature review, the technique of in-depth analysis of the full contents of the articles was used. The primary source of data was the *Web of Science* (WoS) database.

The goal of the SLR was to try to identify, integrate, and assess the current state of research in the area of hydrogen supply chain design. There are three main dots in the systematic literature review process. The first step is to carefully draft a literature review plan, which includes clearly defining the purpose of the study, preparing the study, and producing a protocol for the data to be collected during the study. Stage two involves carrying out the research procedure according to the established, accepted guidelines. It is worth emphasizing that this stage is based on the selection of the research population of articles, the use of quantitative and substantive analysis techniques, and the assessment of the rightness of the choice made. The last, third stage of work is related to the preparation of a report on the conducted research [9]. The SLR contributed to the identification of variables and then allowed for their verification and selection, which in turn contributed to the development of the concept of a structural and functional model.

The literature review was conducted according to the following procedure:

1. On the basis of keywords, according to the adopted research objective, a preliminary content analysis of 311 articles from the *Web of Science* (WoS) database was carried out after prior classification. The articles were identified and classified based on keywords: hydrogen, supply chain, storage, renewables, model, location, grid, and electrolysis;
2. A selection of 42 articles was made, which were identified as key in the study. This selection concerned works in the area of production and storage of hydrogen from RES by electrolysis, the use of fuel cells, the utility use of hydrogen in transport, and modeling of hydrogen supply chains;
3. The selected 42 articles were subject to in-depth substantive analysis. The purpose of this analysis was:
    - To create a structural model, identifying both technical, economic, and logistical factors as well as formal and legal factors;
    - Identification of research methods applicable to modeling the processes of supply, generation, storage, and distribution of hydrogen from RES.

The beginning of the first stage consisted of identifying the main objective and formulating the research questions. The main question was: What is being said about the potential for stabilizing power grids with a hydrogen buffer fed from renewable energy sources?

Detailed research questions were also posed in order to minimize the situation of omitting articles relevant to the main research objective:

- What has been written about energy storage in green hydrogen?
- What methods and models were used to analyze power grid stabilization systems through hydrogen storage?
- What has been written about renewable hydrogen supply chains?
- What criteria for selecting hydrogen storage sites have been discussed in the scientific literature?

Research questions became the basis for the selection of keywords according to which the search in the WoS database was carried out: hydrogen, storage, electrolysis, renewable energy sources, model, energy network, supply chain, and location. The searches were carried out crosswise in four stages, which allowed for the extraction of 311 literature items.

Based on the analysis of full texts from the received database of 311 articles, 42 key items were selected that most closely matched the specific research area. The aim of the second level of the systematic review of the literature was to identify the factors underlying the creation of a structural and functional model of power grid stabilization in the supply chain phase division. These factors were divided into four categories: technical, locational, economic-logistical, and formal-legal.

The results obtained in the form of extracted factors were validated during expert consultations with scientists representing technical and economic sciences and representatives of the power industry.

The panel diagram of the research process is shown in Figure 1.

A systematic review of the literature, combined with the validation of results with scientists and representatives of business practice, allowed to develop the concepts of a multi-criteria theoretical model [10] and a functional model of power grid stabilization using a green hydrogen buffer.

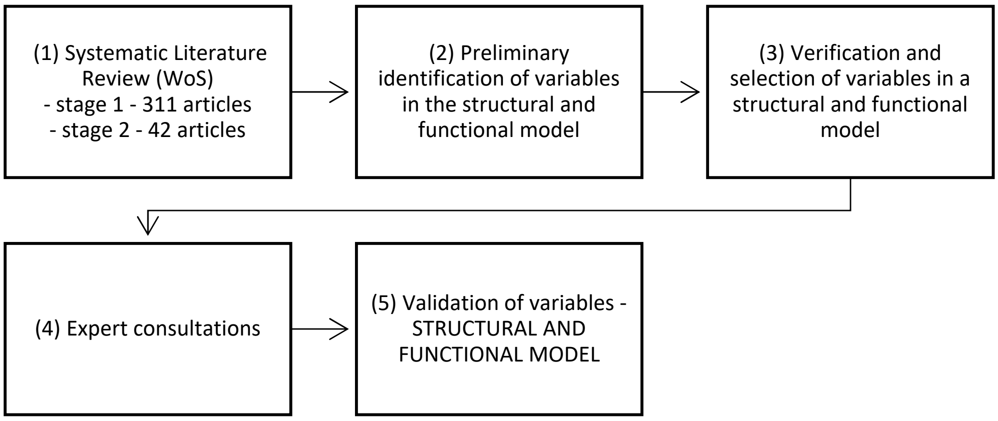

Figure 1. Panel scheme of the conducted research. Source: own elaboration.

3. Results

3.1. Theoretical Background

RES belong to the category of unstable sources, i.e., those dependent on weather conditions, which may lead to a situation of excess or shortage of electricity in the power system. System balancing is possible through long-distance transmission or the use of energy storage technology. The problems with long-distance transmission of energy are manifold: energy is lost during transmission, building new overhead high-voltage lines faces great resistance from local communities, and building underground lines is extremely costly. In this situation, the production of hydrogen from renewable energy and its transmission with an appropriately adapted infrastructure to places where it can be converted back into electricity appears as a solution to these problems. Therefore, in this case, we can distinguish two complementary supply chains: the energy supply chain and the hydrogen supply chain, the structure of which is shown in Figure 2.

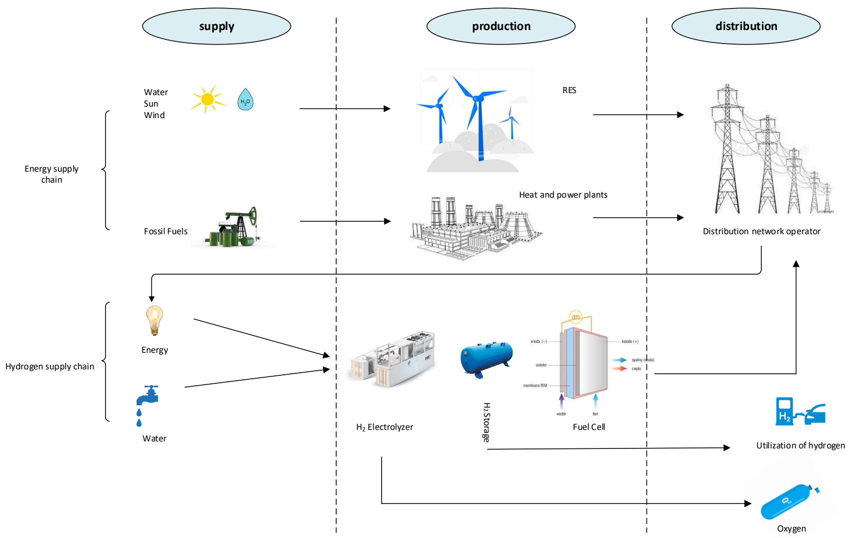

Figure 2. Energy supply chain collaborating with hydrogen supply chain. Source: [7].

Over the last few years, the number of scientific publications dealing with the subject of using hydrogen to store electricity and thus stabilizing uneven energy production from renewable sources has significantly increased. Belmonte et al. [11] considered two alternative integrated power systems: one based on photovoltaic and hydrogen technology (fuel-cell-coupled electrolyzer) and the other based on photovoltaics and batteries. Samsatli S. and Samsatli N.J. [12] created a space-time model of energy systems with detailed consideration of transport and storage (STEMES) containing five components: space, time, resources, technologies, and transport infrastructure. Mukherjee et al. [13] assessed the benefits of power-to-gas energy storage, taking into account the uncertainties in three key parameters that may affect the performance of the energy system: hourly electricity price, number of serviced vehicles with fuel cells, and the amount of fueled hydrogen. Kroniger and Madlener [14] assessed the possibility of storing excess electricity generated in wind farms in the form of hydrogen using the Monte Carlo simulation and analysis of real options, indicating that direct sale of the produced hydrogen is more profitable than storing electricity in hydrogen and re-electrification. Kotowicz et al. [15] performed a technical analysis of efficiency parameters as a function of electric power and identified the energy needs of a system based on a hydrogen generator and a fuel cell. Walker at all [16], using the analytic hierarchy process method (AHP), compared the power-to-gas system with other energy storage technologies, taking into account criteria such as energy transport, its density, and the possibility of seasonal storage. Rezaei et al. [17] carried out a study for 32 cities in Iran to establish an off-grid hybrid wind–solar farm for hydrogen production against a wide range of criteria and then investigated the technical-economic potential of hydrogen production. Kalinci et al. [18] used the hybrid optimization model for electric renewables (HOMER) to determine the optimal equipment size for a hybrid renewable energy system using hydrogen as an energy store. Li et al. [19] developed a comprehensive model to investigate the optimal investment and operation of electrolyzers and hydrogen storage facilities in technical and economic terms. Yang et al. [20] developed an optimization model for a hydrogen supply chain based on an off-grid wind–hydrogen coupling system. Bartela [21] studied the integration of a compressed air and hydrogen storage system in order to efficiently store large amounts of energy. Rahimi et al. [22] made a technical and economic evaluation of a hybrid wind–hydrogen system (wind turbine, electrolysis, and PEM fuel cell) in the household. Similarly, Teichmann et al. [23] proposed liquid organic hydrogen carriers (LOHC) as energy storage in residential and commercial buildings as well as the use of heat generated from a hydrogenation unit and a fuel cell to satisfy the heat demand of these buildings. López González et al. [24] assessed the energy consumption, energy storage density, and energy efficiency of a hydrogen storage connected to a renewable energy system. Three storage technologies (low pressure, metal hydride, and high pressure) were investigated, and the results showed that direct use of hydrogen stored at low pressure is the most energy-efficient option. Yee Mah et al. [25] proposed a cascade analytical approach to planning a self-sufficient, independent energy system that is fully supported by renewable energy sources and a liquid organic hydrogen carrier as an energy storage. Schrotenboer et al. [26], using the theory of Markov decision process, constructed optimal policies for everyday decisions about the amount of energy to be stored as hydrogen or bought or sold at the electricity market and how much hydrogen to sell for use as a gas. Boretti [27] discussed the case of NEOM City—a city in Saudi Arabia that is to be powered exclusively with renewable energy sources— indicating as one of the solutions the use of additional photovoltaic energy from wind and solar for the production of hydrogen using electrolyzers and then partial use of this hydrogen to produce the missing electricity in order to stabilize the network and export its excess. Tarhan and Cil [28] made a theoretical review of the considerations on the use of hydrogen energy in energy storage, limitation in the use of hydrogen, and its future application.

Many articles are devoted to technical issues dealing with hydrogen storage technology. Elberry et al. [29] discussed the possibilities of large-scale compressed hydrogen storage in three categories: storage tanks, geological storage, and other underground storage alternatives. Blacharski et al. [30] indicated technical problems related to the storage and transport of hydrogen, discussing parameters such as viscosity, density, specific heat, Jou-le-Thomson coefficient, flammability, regular combustion rate, minimum ignition energy, etc. Bondarenko et al. [31] discussed the main methods of hydrogen storage (physical—in a compressed or liquefied state; physicochemical—mainly bound in metal hydrides; chemical—in hydrogen chemical compounds, for example in ammonia) and their advantages and disadvantages and related difficulties. Glass et al. [32] investigated the efficiency of a biogenerator transforming hydrogen into electricity. They indicated, inter alia, that idle running for less than half a day does not adversely affect the return to original capacity, while longer periods of inactivity cause a slight temporary reduction in bioreactor capacity.

An in-depth analysis of the literature allowed for an initial selection of factors of the functional model. The extracted factors were assigned to individual phases of the supply chain and to one of the four distinguished categories, as shown in Table 1.

Table 1. Structural model factors derived from the conducted literature review.

Supply Chain Phase	Group of Factors	Factors	Authors
Feedstock	Economic and logistical	• Volume of purchasing energy from res (different for various res); • Volume of water purchases; • Operating costs: energy purchase and transmission costs; • Energy network efficiency indicators.	[13,18,20,22,26]
	Technical	• Daily production volume (main power station/source); • Type/percentage share of RES sources (solar, wind, etc.).	[12,21,25,27]
Production	Economic and logistical	• Operating costs: maintenance costs; • Operating costs: cost of purchasing water; • Operating costs: opportunity costs (lost sales, unused res energy); • Operating costs: costs of producing the hydrogen; • Energy network efficiency indicators; • Operating costs: costs of producing electricity.	[11,19,20,23,28]
	Technical	• H2 production power of the system (maximum value) determined by the PEM electrolyzer; • Amount of (daily) H2 production (real value) determined by the PEM electrolyzer; • Amount of (daily) energy production—output/power of the fuel cell; • Electricity generation efficiency = fuel cell efficiency; • Energy conversion time to H2; • Conversion time of H2 to energy; • Water consumption; • Energy efficiency of hydrogen production; • Energy efficiency of hydrogen compression; • H2 consumption by the fuel cell.	[11,15–17,19,21,24,29,31,32]

Table 1. *Cont.*

Supply Chain Phase	Group of Factors	Factors	Authors
Distribution	Economic and logistical	• Selling price of fuel cell energy (cost of producing energy for own purposes); • Selling price of H2 (production cost of H2 for own use); • Operating (station-keeping) cost; • Average daily demand for electricity on the grid; • Volume of H2 delivered after compression; • Average daily hydrogen consumption.	[15,19,20,26,30]
	Technical	• Station charging time (distribution depot); • H2 refueling time of cars and tankers; • The time of loading and unloading H2 onto the means of transport; • Number of H2 tankers (H2 carriage); • Number of cars on H2 (fleet, capacity); • Number of refueling stations; • Station size (in terms of demand and availability).	[12,17,19,20]

Source: own elaboration.

3.2. Identification of the Stabilization Mechanism

The main purpose of introducing a hydrogen buffer to the energy system (electricity distribution network) is to stabilize the network operation by reducing the energy loss factor, defined as the percentage of energy produced by RES that is impossible to collect and irretrievably lost. In the presented approach, system stabilization is understood as balancing the demand and supply of electricity, taking into account the losses arising in its transmission (energy demand = energy supply − energy distribution losses).

In the short-term context, the purpose of introducing the hydrogen buffer energy system to the electricity distribution network is to increase the reliability and flexibility of the grid operation by influencing:

- Coefficient of smoothing the network load curve on a daily scale;
- Quality parameters of supplied electricity, such as voltage stability, frequency fluctuations, and harmonics level;
- Reduction of the energy loss coefficient defined as the percentage of energy produced by RES that is impossible to collect and irretrievably lost.

These goals can be achieved by effectively managing temporary surpluses of power generated by RES, disturbing the balance of active power. The balance of active power (temporary), taking into account the power generated from RES installations, looks as follows:

$$P_{SEE} + P_{OZE} = P_Z + (\Delta P_{Ln110} + \Delta P_{TGPZ} + \Delta P_{Ln1} + \Delta P_{Ln2} + \Delta P_{Ln3} + \Delta P_{T1} + \Delta P_{T2} + \Delta P_{T3}) \quad (1)$$

where

P_{SEE}—active power flowing from power system (SEE) (through the 110 kV line to the transformer in the 110/15 kV transformer station (GPZ));
P_{OZE}—active power from RES (through the 15 kV line);

ΔP_{Ln110}—active power losses in the 110 kV line;
ΔP_{TGPZ}—active power losses in a 110/15 kV transformer;
ΔP_{Ln1}, ΔP_{Ln2}, ΔP_{Ln3}—active power losses in 15 kV lines;
ΔP_{T1}, ΔP_{T2}, ΔP_{T3}—active power losses in 15/0.4 kV transformers;
P_Z—load active powers at 15/0.4 kV individual stations.

Surplus capacity arises when the amount of power flowing from the power system and RES connected to the MV grid exceeds the demand for active power of consumers and active power losses in transmission and transformation of energy related to this demand:

$$P_{nad} = (P_{SEE} + P_{OZE}) - (P_Z + \sum \Delta P) \quad (2)$$

where

P_{nad}—active power surplus;
$\sum \Delta P$—sum of active power losses in HV and MV lines and transformers related to P_Z demand ($P_Z \times$ energy loss ratio).

For the sake of simplification, it should be assumed that the power surplus relates to energy produced from RES and, when it occurs, the direction of power flow in transformer station; i.e., energy flows from the 15 kV switchgear busbar through the transformer to the 110 kV switchgear busbar. In the system of changing the current flows, the surplus of power is therefore the RES power "transferred" to the high-voltage power grid.

In general terms, the task of energy storage control algorithms is to reduce the negative impact on the power grid caused by fluctuations and dynamic changes in power that resulted from the operation of unstable sources and unstable receivers connected to the LV distribution network and to improve the quality parameters of electricity, especially the voltage profile. The active power balance during the buffer operation is as follows:

$$P_{SEE} + P_{OZE} + P_{FC} = P_Z + \sum \Delta P + P_E \quad (3)$$

where

P_{FC}—active power flowing from the cell fuel;
P_E—active power received by the electrolyzer (unstable surplus energy from RES and energy needed to produce hydrogen for distribution).

The input parameters of the stabilization mechanism formulated in this way are:

- Maximum power of RES installations in the period t + 1 connected to a given transformer station (GPZ);
- Energy production curve in period t connected to a given transformer station (GPZ);
- Projected amount of applicable hydrogen consumption;
- Operating conditions of the buffer installation.

The amount of hydrogen fuel consumption can also be an input parameter as an element of discharging the resulting surplus energy from the storage. In the described mechanism, it is an input parameter due to the assumption that it is the demand for hydrogen fuel that determines the volume of supply.

The procedure for stabilizing the operation of the power grid requires the determination of the forecast surplus of energy from RES, the maximum accumulated energy produced in a continuous period, and the minimum accumulated energy produced in a continuous period. These values will be used to calculate the output parameters of the hydrogen buffer, i.e., the reference volume of energy produced by RES stabilizing the operation of the system, the capacity of hydrogen and oxygen storage, and the power of the electrolyzer and fuel cell.

To this end, the reference volume of energy produced by RES should first be established, stabilizing the operation of the power system assigned to a given transformer station (GPZ):

$$E_{OZE\ REF} = f(E_{OZE}; t) \quad (4)$$

where

$E_{OZE\ REF}$—projected reference volume of energy production from RES in the period t + 1;
E_{OZE}—energy produced by RES in the period t.

Determining a long-term forecast of the reference volume of energy production (stable over time) requires taking into account the expected growth of RES installations connected to the transformer stations (GPZ) and shifting the trend line by the value (or part of the value) of the forecast error. The forecast takes into account the seasonality of energy production from RES. In a short period (running operation of the buffer), the control algorithm should assume maintaining a constant power of the connection point in 1 min periods. The value of the capacity that should be maintained in the next minute should be determined on the basis of the average RES capacity that was registered in the preceding period. The electrolyzer power is determined on the basis of the following functions:

$$P_E = \max(P_{OZE\ MAX} - P_{OZE\ REF} + P_U) \quad (5)$$

where

$P_{OZE\ MAX}$—the maximum active power of the connected RES stations in the period t + 1 or the power rating of the connected RES;
$P_{OZE\ REF}$—forecast reference active power from RES in the period t + 1;
P_U—the active power required for the production of the forecast applicable consumption of hydrogen in the period t + 1.

The determined forecast reference volume of active power flowing from RES takes into account the expected forecast error, which can be treated as a safety margin before the increase in demand for power received by the electrolyzer.

The next step is to determine the power of the fuel cell:

$$P_{FC} = \max(P_{OZE\ REF} - P_{OZE\ MIN} + P_{SOC}) \quad (6)$$

where

$P_{OZE\ MIN}$—actual minimum active power connected to RES stations in the period t + 1;
P_{SOC}—active reserve power enabling emergency unloading of the storage.

In the presented function, the power of the fuel cell concerns only the power shortages that occur; it does not take into account short-term fluctuations in voltage and frequency regulated by the control algorithm. It is assumed that their influence on the cell's power level is negligible.

In a short period, the difference between the power generated by RES sources, measured on the transformer, and the assumed reference (short-term) power is determined. The difference between the reference power and that measured on the transformer is covered from the energy storage. The algorithm should also take into account the maximum allowable change in power so as not to adversely affect the flicker coefficient.

The determination of the hydrogen storage capacity is made on the basis of the power fluctuations in relation to the reference value:

$$HSOC_{MAX} = f(NW_{MAX}; ND_{MIN}) \quad (7)$$

where

$HSOC_{MAX}$—maximum hydrogen storage capacity;
NW_{MAX}—maximum accumulated energy produced in a continuous period;
ND_{MIN}—minimum cumulative energy produced in a continuous period.

When establishing the reference size of the energy storage, the seasonality of the distribution of energy surpluses and shortages above the designated reference value of the forecast should be examined. To that end, a maximum amount of cumulative energy produced in a continuous period and a minimum cumulative energy produced in a continuous period should be established. When verifying the compensation of the accumulated energy of surpluses and shortages in time, the degree of shift of the trend should be verified (when determining the reference level of energy produced by RES). The determined amount of energy (kWh) indicating the size of the storage should be converted into the amount of hydrogen reserve (kg), taking into account the energy efficiency of the electrolyzer.

In the short term, the RES power stabilization algorithm will be initiated when the permissible (limit) power fluctuations at the connection point are exceeded. When implementing this algorithm, it is necessary to maintain a level of charge (SOC) of the energy store that enables both recharging and discharging. Therefore, the algorithm cannot be implemented when the SOC is maximally ($SOC = SOC_{max}$) or minimally ($SOC = SOC_{min}$) filled.

Before starting the process of stabilizing power fluctuations generated by renewable energy sources, the level of charge of the SOC energy storage will be checked. The required SOC level for the implementation of the power stabilization algorithm should take into account the operating conditions of the assumed reservoir (input data). The SOC level so determined enables both the output and the consumption of power by the storage system. If the SOC level is higher than the required level, the storage should be discharged with the power not exceeding the power of the HV/MV transformer until the required SOC level is reached. In case the SOC level is lower than the required energy storage, it should be topped up. When the required SOC level is achieved, the RES power stabilization procedure may be performed.

Additionally, the stabilization mechanism can include the electrolysis by-product, i.e., oxygen. The determination of the oxygen storage capacity is carried out as a function:

$$OSOC_{MAX} = fmax(O_E; O_D) \tag{8}$$

where

$OSOC_{MAX}$—maximum oxygen storage capacity;
O_E—the volume of oxygen produced from the energy received by the electrolyzer in the period t + 1;
O_O—oxygen volume distributed in the period t + 1.

The size of the oxygen storage is the maximum difference between the forecast volume of energy received by the electrolyzer and the forecast volume of oxygen distribution over the same period.

The power system balancing mechanism determines the volume of energy consumed from the high-voltage grid. The volume of energy to be taken from the high-voltage grid results from the power balance indicated in Equation (3):

$$P_{SEE} = (P_Z + \sum \Delta P + P_E) - (P_{OZE\ REF} + P_{FC}) \tag{9}$$

The volume of energy to be taken from the HV grid is determined taking into account the seasonality of the load curve. This stage ends with the stabilization mechanism of the power grid.

4. Discussion

In the long term, the task of the hydrogen buffer is to stabilize the operation of power grids by converting excess electricity into hydrogen (electrolyzer), storing hydrogen (storage), and converting hydrogen into electricity (fuel cell). The energy stored in the hydrogen will serve to meet future demand in the event of periodic shortages. Moreover, as a hydrogen fuel (distribution phase), it can also be used for the utility purposes of DNO (e.g., refueling the vehicle fleet). Oxygen is a by-product of the electrolysis process, the sale of which may be a source of DNO revenues in the future (additional economic benefits).

Due to the complexity and interdisciplinarity of the research issues, the supply chain structure was adopted in the assumptions of the proposed stabilization concept, which allowed for the identification of the supply (1), production and storage (2), and distribution

(3) phases. The developed concept of the operation of the power-grid-stabilization system in terms of the supply chain phases in DNO's operations is shown in Figure 3.

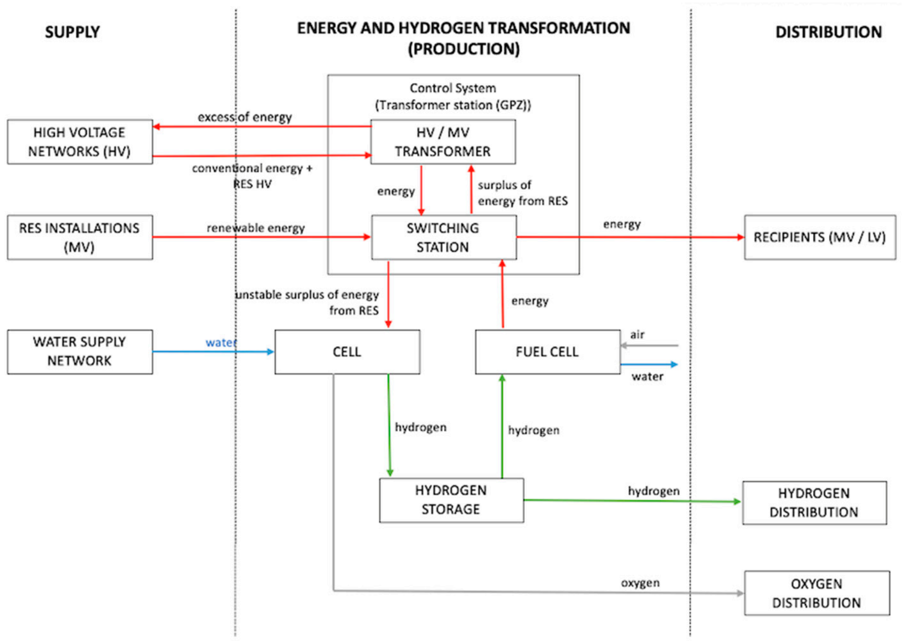

Figure 3. The concept of stabilizing the operation of power grids in the phase system of the supply chain. Source: own elaboration.

In the concept of stabilizing the operation of power grids presented in Figure 3, it was assumed that the main factor destabilizing the operation of the grid in the long term is the surplus of energy from RES (supply phase). In the event of a surplus, it is transferred from the MV line to the HV line (the surplus is reduced by the energy losses occurring in the transmission). This is a disadvantageous phenomenon because, apart from destabilizing the operation of power grids, it may ultimately result in the necessity to incur significant investment outlays for the modernization of power lines (HV).

The systematic review of the literature allowed to distinguish two main trends in the considerations: the design of the power system based on the hydrogen buffer and the current operation of this system. Designing is a wider issue and has been examined in a separate article discussing the assumptions of the functional model of the power system based on the hydrogen buffer [10]. The functioning of the power system based on a hydrogen buffer concerns, in particular, technical and economic factors, and for the system design, it is a starting point for calculating the power of the buffer together with the capacity of the hydrogen storage. Separated variables of the functional model of power grid stabilization, divided into controllable, uncontrollable, and disturbing variables in the phase and factor matrix system, are presented in Table 2.

Table 2. Functional model factors derived from the conducted literature review.

Supply Chain Phase	Factor Group	Factor	Unit	Type
Feedstock	Technical	Installed capacity of res	Mw	Non-controllable
		Structure of RES power	%	Non-controllable
		Losses of RES power in 15 kv lines	Kw	Disturbing
	Economic-logistical	Volume of RES-generated electrical energy	Mwh	Non-controllable
		Volume of water delivered	L/kg	Non-controllable
		Volume of electricity released from MV grid to HV grid	Mwh	Disturbing
		Energy purchase costs to cover the balance difference	EUR	Non-controllable
Production and storage	Technical	Pem electrolyzer power	Kw	Controllable
		Electrolyzer efficiency	Kwh/kg	Non-controllable
		Fuel cell power	Kw	Controllable
		Fuel cell efficiency	Kwh/kg	Non-controllable
		Hydrogen storage capacity	Kg	Controllable
		Hydrogen storage throughput	Kg/h	Controllable
	Economic-logistical	Operating costs of the production phase	EUR/year	Non-controllable
		Demand of main power station for electricity from the fuel cell	Mwh	Non-controllable
Distribution	Technical	Distribution capacity	Kg/h	Controllable
	Economic-logistical	Operating costs of the distribution phase	EUR/year	Non-controllable
		Revenues from the sale of oxygen	EUR/year	Non-controllable
		Demand for hydrogen fuel	Kg/24 h	Non-controllable

Source: own elaboration.

By isolating the model factors and establishing the stabilization mechanism, some simplifications and assumptions were made:

1. The only analyzed factor destabilizing power grids in the long term is the surplus of energy from RES;
2. The model does not include the estimation of energy shortages. They will be compensated as part of the buffer controlling algorithm;
3. The volume of renewable energy is estimated on the basis of forecasts taking into account historical data and the structure of the types of individual renewable energy sources. The model does not take into account weather factors;
4. The model concerns renewable energy sources connected to the medium-voltage grid, the surplus production of which goes to the high-voltage grid. In the case of RES connected to the high-voltage grid, the buffer located at the transformer station (GPZ) does not affect the level of the used transmission capacity of the HV cable and the transformer power;
5. The storage control algorithm (in the short term) provides for maintaining the buffer charging level within the assumed minimum and maximum values regardless of the volume of energy fluctuations from RES;
6. Due to the fact that a single storage system will perform several system services, it is necessary to prioritize the operation of the available algorithms. Of the necessary algorithms, only one of the highest priority algorithms can be implemented;
7. The demand for hydrogen fuel is met within the framework of a stable (reference) energy from RES;

8. The algorithm assumes the stabilization of the network through a hydrogen buffer, taking into account the seasonality of supply and demand on an annual, weekly, and daily basis.

5. Conclusions

Due to the growing level of energy produced by RES, the issue of stabilizing the energy network is becoming increasingly important for energy network distributors. This article presents the conceptual assumptions of the research on the design of a functional multi-criteria model of the stabilization model architecture of energy distribution networks based on a hydrogen energy buffer, taking into account the applicable use of hydrogen. The research aimed to identify the variables contributing to the stabilization of the operation of distribution networks based on a systematic review of the literature and expert consultations. The novelty of the elaborated concept of a functional model was a holistic approach combining two dimensions in which the identified variables were embedded. The first dimension covers the phases of the supply chain: procurement and production along with storage and distribution, while the second dimension divides the separate factors into technical, economic, and logistic. The study adopted the perspective of a distribution network operator. In the concept of stabilizing the operation of power grids (Figure 2), it was assumed that the main factor destabilizing the operation of the grid in the long term is the surplus of energy from RES (supply phase). In the case of a surplus, it is transferred from the MV line to the HV line (the surplus is reduced by the energy losses occurring in the transmission). This is an additional disadvantage because, apart from destabilizing the operation of power grids, it may ultimately result in the necessity to incur significant investment outlays for the modernization of power lines (HV).

As a result of the research, several benefits of stabilization using a hydrogen buffer from the perspective of the distribution network operator were identified. These include:

- The possibility of avoiding the costs of investments in HV associated with the need to modernize the line in order to transmit the surplus energy produced by RES connected to the MV;
- The possibility of avoiding investment costs in new/modernized HV/MV transformers with higher power or the possibility of reducing the power of already-installed HV/MV transformers due to the regulation of power fluctuations and voltages;
- Reduction of losses/obtaining revenues related to the undeveloped surplus of energy from RES by compensating for power shortages and/or distribution of hydrogen;
- Obtaining white certificates for the achieved energy effect;
- Revenues from the distribution of oxygen, which is a by-product of electrolysis.

The contribution of the presented research may be of particular importance for energy distribution system operators, as several benefits have been identified as a result of the development of a system solution that stabilizes the operation of power distribution grids. Furthermore, the model may be used in designing solutions stabilizing the operation of power grids in which there are surpluses of electricity produced from RES. Due to the applied multidimensional approach, the developed model is recommended for use as it enables the design of solutions in a systemic manner.

As the research presents the conceptual assumptions for a functional model of power grid stabilization in the green hydrogen supply chain system, it has some limitations. They are mainly related to the necessary simplifications and assumptions made by isolating the model factors and establishing the stabilization mechanism. In order to develop the model, seven assumptions were made, which are listed in Section 4. Another limitation of the practical use of the model is the focus on identifying variables and the stabilization mechanism itself. The study does not determine their impact on the effectiveness and efficiency of the functioning of the energy system. This is a further direction of research that should be followed in the next step to increase the application aspect of research. Finally, the study does not take into account the power supply to the grid from small RES installations. Their share in energy production is constantly increasing and is also a factor destabilizing the operation of power grids.

Considering the above-mentioned limitations, however, it can be stated that the identified functional model factors derived from the literature review make it possible to optimize the parameters of the green hydrogen supply chain, with particular emphasis on the supply and distribution phase. The next step in the research is a multi-faceted assessment of the possibility of creating buffers based on hydrogen storage at significant supply points. The assessment will consider especially economic and social aspects while assuming the possibility of applicable consumption use of hydrogen as a fuel.

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