Environmental and Climate Technologies
2025, vol. 29, no. 1, pp. 809–821
https://doi.org/10.2478/rtuect-2025-0054
https://content.sciendo.com

Forecasting the Impact of Wind Power Expansion on Latvia's Electricity Supply and Demand Balance

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Received 23.04.2025; accepted 04.09.2025

Abstract **– Globally, including in Latvia, the production of renewable electricity is increasing. In the near future, rapid development of wind power plants (WPP) is expected in Latvia, significantly increasing the existing capacity of WPPs. To effectively plan the development of the electricity supply system, it is necessary to forecast the potential amount of electricity that will be generated by the planned WPPs. As part of this study, calculations were made for the potential electricity production from onshore WPPs in Latvia, using available data on average wind strength and planned WPPs. The results show that by implementing the planned capacity of 791.9 MW of WPPs, the electricity generated by WPPs will increase by 2.4 TWh per year. Meanwhile, achieving the 2050 target (4.5 GW installed onshore capacity), approximately 15.3 TWh of electricity will be generated annually by WPPs. The planned electricity volumes from WPPs significantly exceed the current electricity demand in Latvia, therefore, solutions for balancing electricity demand and supply in the future need to be found.**

Keywords **– Electricity demand; hydrogen; renewable electricity; wind power plants; wind energy.**

1. Introduction

The European Union (EU) is committed to becoming the first climate-neutral continent by 2050 [1]. To achieve this goal, it is crucial to increase the share of renewable energy across all sectors, including renewable electricity generation. As assessed by the International Energy Agency (IEA), while the growth of renewable electricity generation is significant in several parts of the world, overall, the increase in global electricity demand exceeds the growth rate of renewable energy electricity generation [2].

To promote renewable electricity generation, a clear political vision and data-driven decision-making based on the actual situation are necessary. Analysing electricity generation data helps to understand the share of electricity produced from renewable and fossil energy sources. This, in turn, makes it possible to assess the resulting greenhouse gas (GHG) emissions and their impact on the environment. Consumption trends highlight opportunities and needs – where, with which technologies, and during which periods it is particularly necessary to promote and optimize renewable electricity generation. This ensures that the produced electricity is used efficiently, aligning it with consumption patterns (or vice versa). Such an approach can help reduce energy losses and peak loads, allowing for the planning of economically sound investments in the sector.

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The availability and utilization possibilities of renewable energy resources vary across different regions of the world. For example, in Latvia, a significant source of electricity generation is rivers rich in water, with hydropower plants (HPPs) built on them. The three largest HPPs on the Daugava River have a total generating capacity of 1558 MW [3], and during the spring months, this is often sufficient to produce more electricity than is consumed in Latvia. In contrast, the neighbouring countries Estonia and Lithuania do not have such large HPPs, and other energy resources such as wood chips and waste (Combined heat and power plants (CHP)), wind and solar, are more relevant there [4], [5].

To assess Latvia's current state of electricity generation, it is necessary to compile detailed data on existing electricity generation and consumption across different time periods. Latvia's transmission system operator, JSC 'Augstsprieguma tīkls', collects and publishes hourly electricity generation and consumption capacity data [6]. The largest proportion of the electricity generated is provided by HPPs, which accounted for 54 % of the total electricity produced in 2024. During the winter months, natural gas also plays a significant role, contributing 27 % of electricity generation in 2024 (see Fig. 1). This is partly due to the simultaneous production of heat energy, which is in higher demand during winter, considering Latvia's climate.

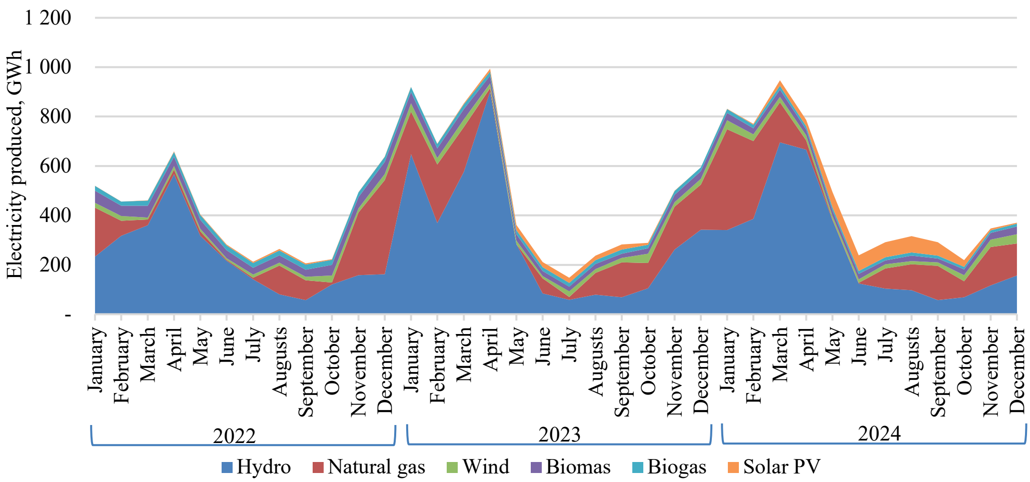

Fig. 1. The volume of electricity produced and fed into Latvia's power grid in 2022–2024 by resource, GWh [6].

As shown in the Fig. 1, the electricity generation profile remains similar each year. However, depending on specific weather conditions, the actual electricity generation volumes vary. In 2024, solar PV electricity generation increased sharply, reaching 7 % of the total annual electricity production (see Fig. 1) and exceeding the volume of electricity generated from wind energy, which is developing slowly in Latvia. It should be noted that the actual amount produced from solar PV is even higher, as the system operator has data on electricity fed into the grid but lacks information on electricity that is generated and consumed immediately on-site.

Although Latvia has a high potential for wind energy, electricity generated from wind energy in 2024 accounts for only 5 % of the total electricity fed into the Latvian grid. It is expected that the volume of electricity generated by wind energy in Latvia will significantly increase, as several wind farms are now being planned. Currently, there is a reserved capacity of 791.9 MW for wind farm construction (onshore) with the transmission system operator [7], and the total capacity is expected to reach 5.5 GW in 2050 (1 GW offshore and 4.5 GW onshore) (for comparison, the current total wind energy capacity in Latvia is only 133 MW) [8]. It should be noted that mentioned estimates do not include hybrid projects where WPPs are implemented in combination with solar power plants and/or storage systems.

The increase in wind capacity will significantly impact the electricity generation profile in Latvia. Therefore, it is already essential to perform calculations and forecasts on how the volume of electricity produced will change, to effectively plan how to utilize this valuable resource. While previous studies have evaluated the potential of WPP in Latvia [9], the possibility of exploiting residual electricity from WPP has not yet been analysed. Within the framework of this study, a comprehensive analysis of international scientific publications, planning documents, and statistical data has been conducted to assess the potential impact of wind power plants (WPP) on the electricity generation and consumption balance in Latvia, including the consideration of various balancing solutions.

This study is structured as follows: following the introduction, which explores the current electricity generation profile in Latvia, the methodology section outlines how the potentially generated electricity volume from WPPs will be calculated. In the discussion section, various options for balancing electricity supply and demand are described. Finally, the conclusion summarizes the key findings and define the questions for further research.

2. METHODOLOGY

Within the framework of this study, a widely used methodology, as reflected in the reviewed literature (including case studies from different countries, for example [10]–[12]) has been employed. To date, this methodology has been primarily applied to assess electricity generation, in contrast, in this study it is adapted to analyse residual electricity resulting from increasing WPP capacities. The methodology described in this section can be applied anywhere in the world, if the necessary data are available. The methodological algorithm presented in this chapter is illustrated in Fig. 2.

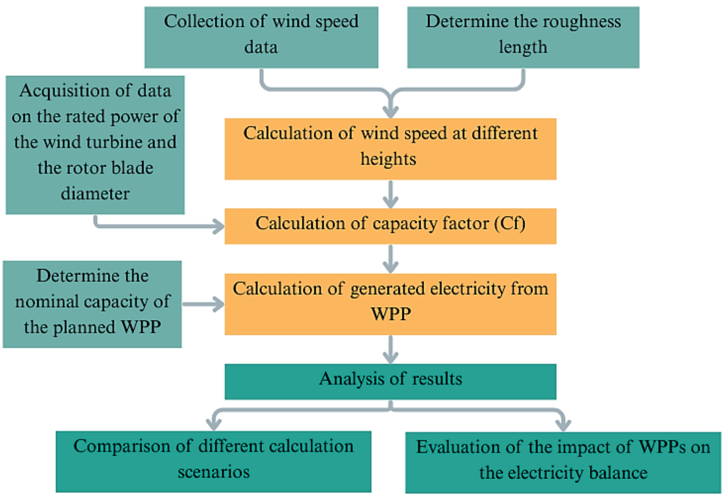

Fig. 2. Methodological algorithm developed and applied in research.

The acquisition of wind speed data constitutes a critical initial step for the calculations, as illustrated in Fig. 2. Several publications in scientific literature explore the wind energy potential in specific areas. That mainly depends on the land use type of the planned location, the height of the wind turbines, and the average wind speed at the corresponding height [10]–[12].

To ensure that the calculation and forecast data on wind speed at a certain height are more accurate, it is recommended to use as much available historical wind speed data as possible [11]. It should be noted that wind data are often measured at stations relatively close to the ground, at building height, and data on wind speed above 200 m are rarely available. Therefore, wind speed at specific height needs to be calculated using existing data and the logarithmic law [10], [12], [13]. The logarithmic law, or logarithmic wind profile, is a mathematical model used to calculate wind speed at height z if the wind speed at a reference height is known. To determine wind speed at height z, use Equation (1):

$$v = \frac{v_{\mathrm{ref}} \times \ln \frac{z}{z_0}}{\ln \frac{z_{\mathrm{ref}}}{z_0}} \tag{1}$$

where

v wind speed at height z, m/s;
v_{ref} wind speed at reference height z_{ref}, m/s;
z height above the ground at the planned wind speed v, m;
z_{ref} reference height at which the wind speed is equal to v_{ref}, m;
z_0 roughness length, m.

The roughness length, which is the theoretical height above the ground where the wind speed is zero, varies across different areas, ranging from 0 to 1.5 [14] (Kurzeme has both large forests and agricultural land, water bodies, cities, villages, etc.). The Danish technology catalogue and other online resources indicate the roughness length depending on the land morphology [15], [16].

In Latvia, wind speed data is collected by the Latvian Environment, Geology, and Meteorology Centre (LVĢMC), whose website provides archived data on hourly wind speeds from several observation stations across the country [17]. However, detailed wind speed data for higher altitudes, such as 100 m, 185 m, or even 300 m, is not freely available as open data in Latvia. The data available on the LVĢMC website reflects information on wind speed at ground level. Therefore, it is assumed that the specified wind speed corresponds to a height of 10 meters. To obtain wind speed data for altitudes up to 300 meters, calculation using Eq. (1) was required.

Of the total reserved capacity for the installation of wind power stations, only one station is located outside the Kurzeme region (in Vidzeme, with a reserved capacity of 110 MW) [7]. Therefore, for the calculations, it is important to obtain data on wind strength in the Kurzeme region. Data for the study was obtained from four meteorological stations in region.

Data from the respective stations includes actual wind strength recorded every hour. Data from 2015 to 2024 has been compiled to determine the average actual wind strength per month. Only data from the relevant years with complete and reliable records were used. The available data (as shown in Fig. 3) indicates that wind strength has increased over the past 4–5 years, which could be attributed to changes in large-scale atmospheric circulation patterns, more frequent cyclonic activity over the Baltic Sea, and regional climate variability possibly linked to climate change impacts in the North Atlantic region [18], [19].

The analysis of monthly data examining the average wind strength for each calendar month shows that wind strength is higher during winter, spring and autumn months, leading to greater potential for electricity generation. In contrast, wind strength is lower during the summer months. Additionally, it is evident that the wind strength at the Ventspils observation station, which is located by the sea, is higher compared to inland areas.

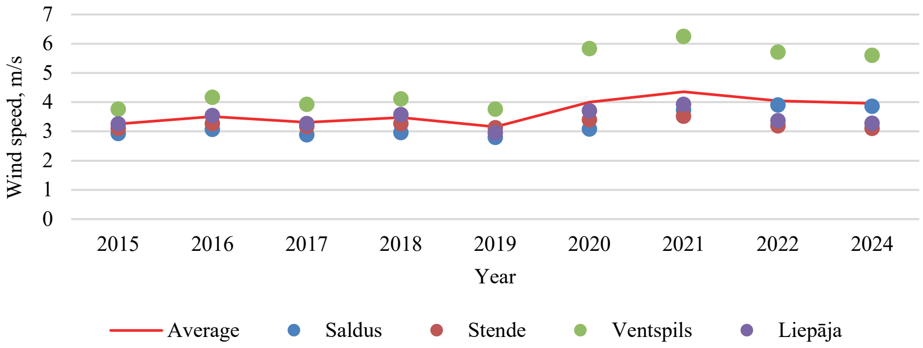

Fig. 3. Average wind speed (m/s) at the selected meteorological stations (assumed height 10 m) [17].

Since the planned WPPs are in various places across region, including areas closer to the sea, the average data from all four stations was used for further calculations. To estimate wind speed at different heights, data on the average wind strength for each calendar day was compiled (average values from all four measurement stations over the period from 2015 to 2024).

A roughness length of 0.4 was chosen based on the values and descriptions provided in [15], [16], selecting the most suitable one that characterizes the Kurzeme region (forests, fields, rural buildings). The reference height, as mentioned before, was assumed to be 10 m, as there is no information on the exact height above ground of the measurement stations. Accordingly, calculations were performed using Eq. (1), and the results are presented in Fig. 4.

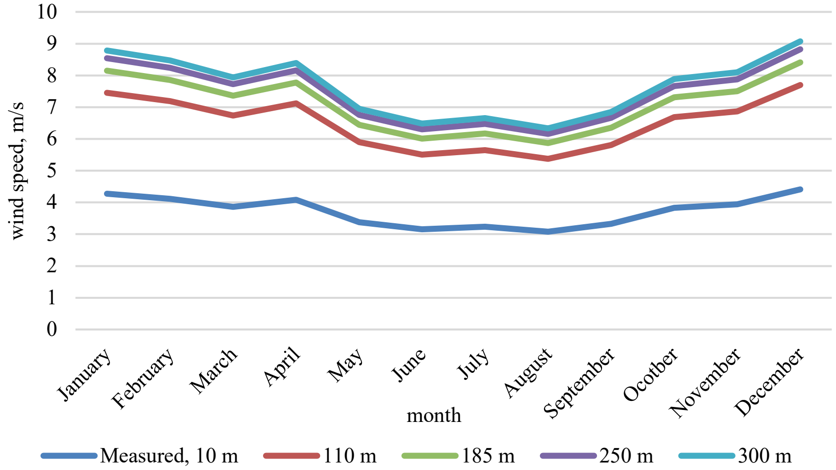

Fig. 4. Wind speed at different heights.

Consequently, after analysing wind data and performing the necessary calculations for the average wind speed at a given height, further steps can be taken to estimate the potential electricity generation. A key parameter for these calculations is the capacity factor (Cf), which represents the ratio of the actual electricity produced over a period to the amount that could be generated if the turbine operated continuously at full capacity [20], [21].

It is well known that WPPs cannot operate continuously at full capacity, mainly due to the variability of wind speed. The capacity factor provides an average measure of how much energy a turbine will generate compared to its maximum potential. To improve calculation accuracy, the study [13] recommends determining the capacity factor for each wind speed rather than using a single average value.

The capacity factor *Cf* is calculated using Eq. (2):

$$Cf = 0.087 \times V_{\mathrm{m}} - \frac{Pr}{D^2}, \tag{2}$$

where

Pr rated power of the wind turbine, kW;
D rotor blade diameter, m;
V_{m} wind speed, m/s.

On average, the annual capacity factor for a wind turbine is between 40–50 % [22], though it can vary more widely depending on wind speeds. Using the given formula and the previously described wind data, the capacity factor (Cf) was calculated for each calendar day. The annual average at a height of 185 meters in Latvia (Kurzeme) was found to be 0.39.
In the calculation formula, the wind speed used was the daily average wind speed, while the turbine's rated power and blade diameter were taken from the Danish Technology Calendar – 140 m diameter and 4500 kW nominal power [15].

Consequently, once the mentioned factor has been calculated, it is possible to determine the total amount of generated electricity (potential) using a simplified equation (3):

$$E = P_{\mathrm{rated}} \times Cf \times T, \tag{3}$$

where

E generated electricity amount, MWh;
P_{rated} nominal capacity of the WPP, MW;
Cf capacity (power) factor;
T time, h.

Accordingly, considering that a total of 791.9 MW of WPP capacity (P_{rated}) is planned for development, calculations have been carried out for the wind energy generated each calendar day, resulting in an annual production of 2383 GWh of electricity from the planned 791.9 MW WPP.

To compare and assess future potential, calculations were also performed for the projected installed capacity on land for the year 2050 [8] and at height 300 m. Additionally, to assess the benefits of increasing rotor diameter and turbine capacity, a calculation was performed for a turbine with a rotor diameter of 160 m, which is currently the most common type of onshore turbine [23]. As an example, a capacity of 4600 kW was used, referencing an actual WPP available on the market (Enercon E-160 EP5 E1) [24]. Calculations for potential energy from offshore WPP are not conducted at this research. The obtained results are summarized in the following section.

3. Results

Based on the methodology described in the previous section, the potential amount of electricity generated by WPPs with a total capacity of 791.9 MW was calculated. To assess the impact of turbine height, rotor diameter, and capacity, calculations were performed for multiple potential scenarios referred in Table 1.

TABLE 1. INFORMATION ON THE INPUT PARAMETERS OF THE SCENARIOS

Scenario	Hub height, m	Rotor diameter, m	Nominal power, kW
Scenario 1	185	140	4500
Scenario 2	250	140	4500
Scenario 3	300	140	4500
Scenario 4	300	150	4600

The main variable parameter in the calculation of the generated electricity volume is the capacity factor, which is directly dependent on the wind strength. As seen in the calculations of Scenario 4 (Fig. 5), the selected wind turbine parameters – nominal capacity and rotor diameter – also have an impact. Thus, the resulting amount of electricity ranges from 2697 GWh per year in the baseline scenario (Scenario 1) to as much as 3382 GWh per year in the fourth scenario. In future studies, it is necessary to examine whether it is rational from a financial and environmental challenge perspective to build taller wind power plants (WPP), considering the potential benefits compared to shorter WPP.

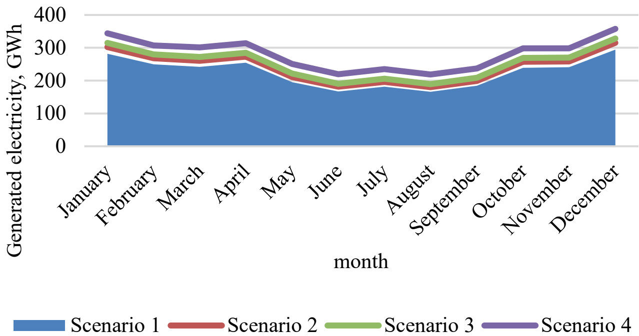

Fig. 5. Potential wind power electricity generation – comparison of four scenarios.

The main variable in calculating electricity generation is the capacity factor, which depends directly on wind speed. In the further analysis, the data obtained from calculations using the wind turbine parameters of the first scenario will be used, as such (and similar) turbines are currently the most widespread and technologically more accessible. Moreover, as Fig. 5 illustrates, the amount of electricity produced will be lower in the summer and higher in the winter. This relationship is strongly tied to wind speed, which is generally lower in the summer. The Energy Strategy of Latvia has assessed that by year 2050, the installed capacity of onshore wind turbines will reach a total of 4.5 GW. Accordingly, using the existing calculated data on wind strength at a height of 185 m and the capacity factor at 185 m (Scenario 1), the potential amount of wind energy generated by wind turbines with a total nominal capacity of 4.5 GW was calculated. The calculation shows that from onshore WPP, a potential of 15.3 TWh of electricity could be generated (for comparison, the current electricity consumption in Latvia is approximately 7 TWh per year) [8]. The obtained results are displayed in Fig. 6.

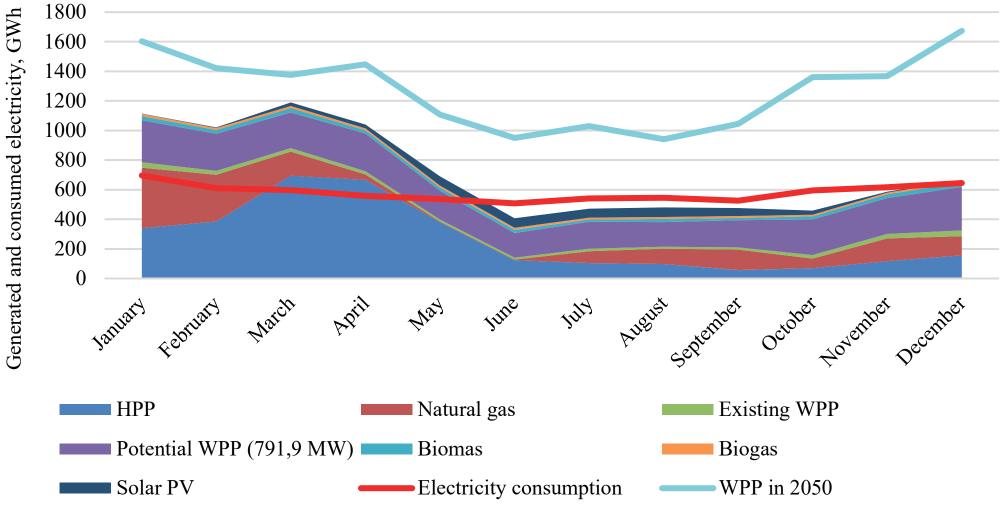

Fig. 6. The generated electricity volume by source and consumed electricity including actual data for 2024 [25], and calculated data for potential electricity from WPP (791.9 MW), as well as the WPP forecast for 2050.

The potential power generation from the planned WPPs with a nominal capacity of 791.9 MW will not be enough to cover the current electricity demand during the summer and fall months, as illustrated in the results summary in Fig. 6. In the spring months, a significant share of Latvia's electricity is supplied HPPs, resulting in electricity production exceeding consumption. Accordingly, it is still necessary to look for solutions to cover the shortfall in electricity production during the summer and autumn months. One solution that works well for reducing load differences is use of BESS. With the introduction of additional WPPs and an increase in surplus electricity generation, it will be important to find solutions for the efficient and economically justified use of electricity.

As indicated earlier, the calculations show that by 2050, with a total of 4.5 GW of installed WPP capacity, the annual electricity generation from WPPs will exceed 15 TWh, which is more than twice the current electricity consumption (this is also visible in Fig. 6). However, Latvia's Energy Strategy [8] forecasts that by 2050, electricity consumption will almost triple, meaning that new electricity consumers will need to be identified.

4. Discussion

With the development of renewable resources-based electricity generation, it has been observed that during certain times of the day, a significant surplus of electricity becomes available, resulting in low electricity prices. Conversely, during other periods, generation is insufficient to meet national consumption needs, requiring electricity imports from other countries. While an open electricity market enables flexibility in covering these gaps, relying on imports may still pose challenge, especially when generation capacity also becomes constrained in neighbouring countries, leading to electricity prices rise and potential supply risks.

Since the availability of renewable resources cannot be controlled, effective solutions must be found to utilize available electricity. For example, in 2016, over 49.7 TWh of electricity generated by wind farms in China was not utilized [26]. Substantial volumes of surplus electricity that are not utilized efficiently have also been observed in other countries with advanced renewable energy generation infrastructure. For instance, in Germany, as early as the beginning of the previous decade, the annual surplus electricity generated from renewable energy sources (RES) reached 421 GWh [26]. The study [27] indicates that, over a 20-year horizon, approximately 25 % of the potential output from WPPs could remain unutilized unless effective demand-side management strategies or new, efficient energy storage solutions are developed. However, in practice, there are several approaches available to balance consumption loads or align them with generation profiles as summarized in Fig. 7.

Currently, given the significant increase in renewable electricity generation capacity, the development of the hydrogen sector is becoming an increasingly important issue. Electricity can be used in hydrogen production through the water electrolysis process (power-to-hydrogen) [28], [29]. If the electricity is derived from renewable energy sources, the hydrogen produced is referred to as 'green hydrogen,' which is expected to play an increasingly significant role in the decarbonization of various energy-intensive sectors.

Hydrogen has several advantages compared to petroleum products – it burns more efficiently and produces significantly fewer emissions (in vehicles). Hydrogen can also be used in residential heating solutions and large-scale district heating systems [30]. When hydrogen is burned, the heat produced is 142.26 kJ/g, compared to 43.1 kJ/g for petroleum fuels and 17.57 kJ/g for wood [31]. Hydrogen is less toxic than gasoline or methane [30]. However, its production is energy-intensive, and the efficiency of electrolysis equipment remains relatively low.

Hydrogen technologies, including those on the consumption side, have not yet reached widespread commercialization and remain costly. A review of various planned and ongoing projects in the Netherlands [32] reveals that none of them can develop without government support, indicating that the sector's development is not yet commercially viable. However, given the forecasts for hydrogen development [33], it will be necessary to significantly increase electrolyser production capacity and develop hydrogen transportation infrastructure. It could be expected that electrolyser costs, as well as the costs of hydrogen storage and transportation technologies, will decrease in the future.

Despite the mentioned challenges, the International Energy Agency forecasts that global hydrogen use will increase from less than 90 Mt in 2020 to more than 200 Mt by 2030. It is estimated that 70 % of this will be low-carbon hydrogen, approximately half of which will be produced through the electrolysis process [33]. Accordingly, in the future, hydrogen production will become a significant consumer of electricity, which should be carefully considered now when planning the development of electricity systems and production facilities. Hydrogen development is also gradually being planned in Latvia [34], and, as a result, electricity demand is expected to increase.

Several studies have examined the conversion of electricity into gas (power-to-gas, P2G), primarily through hydrogen production via electrolysis, with subsequent use in biomethane production [26], [35]–[37]. The resulting gases can be utilized in various applications – for instance, biomethane can replace natural gas by being injected into existing gas infrastructure and used to support various processes. These gases can also serve as energy carriers in the transport sector [36]. For example, a study conducted in Switzerland estimated that up to 2.5 TWh of hydrogen could be produced from 4.5 TWh of surplus electricity that could not be exported (due to simultaneous excess generation in neighbouring countries), without accounting for additional losses from storage and transportation [35]. The immediate use of surplus electricity – such as through hydrogen production – also contributes to grid stability by helping to balance electricity supply and demand in real time [35].

Currently, commercially developed and available technologies include battery energy storage systems (BESS), which vary in capacity and power. BESS are highly efficient (around 90 %), but their capacity decreases over time and losses increase. The materials used in their production, such as lithium, are costly, and their availability is limited. However, research continues to reveal various new types of batteries, and efforts are underway to find new, sustainable materials for their production [38]. In the context of BESS, the role of electric vehicles (EVs) also emerges. EVs can be charged when electricity is abundant and prices are low, and when electricity prices are high, they can discharge electricity back into the grid, like standard BESS [39].

In Latvia, with the increasing production of renewable electricity, there is growing interest in storage solutions, and the installation of energy storage systems is rising. In the first half of 2024, the Construction State Control Bureau of Latvia issued 20 permits for the installation of energy storage systems (136.09 MW) and 24 hybrid permits, combining both electricity generation systems and storage, with a total permitted production capacity of 318.26 MW [40].

Electricity can be used for the electrification of various industrial and energy sectors. The district heating sector is a significant consumer of energy resources across the EU. The electrification of the district heating sector in Europe has been recognized as one of the strategies to help achieve the EU's climate goals [41]. In Latvia, fossil resources (primarily natural gas) are still widely used in the district heating sector, but Latvian heating companies have expressed their readiness to move towards electrification. Electrification of district heating will allow for more efficient use of the existing electricity supply infrastructure. Furthermore, with the introduction of new and more powerful technologies (such as high-capacity heat pumps) to the market, heating costs could potentially decrease in the future [42].

Demand response schemes will play a crucial role in the development of smart grids and in balancing electricity supply and demand. Demand response is characterized by various actions – such as reducing peak loads, shifting load profiles, and optimizing energy consumption. For users who agree to participate in demand response, it provides an opportunity to reduce electricity costs, while system operators can ensure efficient and reliable grid operation [43].

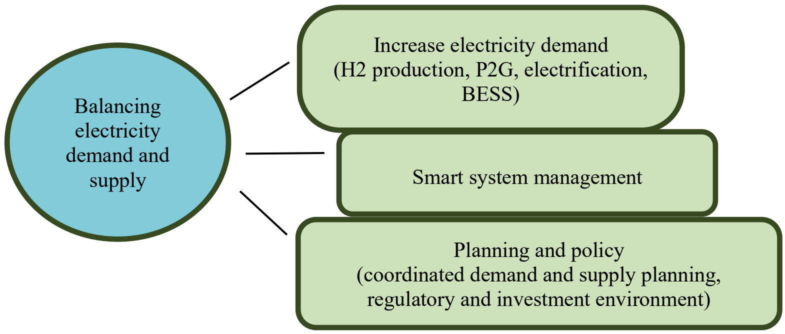

Fig. 7. Summary of solutions for promoting the more efficient use of WPP surplus electricity [25]–[42].

By combining all the solutions, smart management of the entire system and networks is particularly important. Based on accurate actual data and forecasts, electricity consumption can be regulated through demand response solutions, heat energy, hydrogen, and other valueadded products can be produced, electricity can be stored in batteries, or electricity generation can be controlled where possible to make it as economical as possible and to ensure that energy resources are used optimally, without generating surplus energy that is not used efficiently. Additionally, electricity consumers and households are being given increasingly wider opportunities to participate in the electricity market, facilitated by various EU reform directives and regulations [44].

There is no single most suitable method for balancing electricity production and consumption as seen in Fig. 7. The most appropriate solutions vary between different countries and even regions within a single country. Integrated solutions need to be developed, combining all the previously mentioned elements in various combinations and generating new solutions. It is essential to develop potential action scenarios, which can then undergo technical-economic calculations, socio-economic impact assessments, and life cycle analyses for different technological solutions. By combining various factors, in literature it is widely recommended to apply multi-criteria decision-making analysis [45], [46].

5. CONCLUSIONS

Currently, in Latvia, the amount of electricity generated during the spring and winter periods exceeds the demand. With a significant increase in the electricity generated from WPPs in the future, it is expected that the volume of surplus electricity will rise. Accordingly, it is necessary to explore ways to increase electricity demand in a technically and economically justified manner, while ensuring the sustainability of the energy supply.

In general, as described in the previous section and shown in Fig. 7, it can be concluded that the solutions for the effective use of surplus electricity from WPP can be grouped into three categories:

1. Increasing electricity demand (P2G, sector electrification (e.g., district heating), and BESS);
2. Implementation and use of smart energy (and electricity) systems, utilizing various smart management solutions, smart grids, demand response;
3. Policy and planning approaches, carefully coordinating the development of electricity production and consumption from the outset to create an attractive investment environment.

Considering that Latvia is a small country, closely connected with Estonia and Lithuania in terms of energy supply, future studies should also examine the electricity production profiles of Lithuania and Estonia, as well as their plans, as there are potential opportunities to use or store Latvia's future surplus electricity there.

Overall, future studies should conduct a more in-depth analysis to identify the most suitable solutions for balancing electricity supply and demand in Latvia, considering the current and planned electricity production structure, particularly the anticipated increase in electricity volume from WPPs. It is recommended to perform MCDA, incorporating technical, economic, environmental, and social aspects.

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