ASSESSMENT OF NATURAL AND INDUSTRIAL RESOURCES FOR GREEN HYDROGEN INDUSTRY DEVELOPMENT IN THE BALTIC STATES

Ilgmars Lejnieks, Modrite Pelse
Latvia University of Life Sciences and Technologies, Latvia
ilgmars.l@gmail.com, modrite.pelse@lbtu.lv

Abstract. The UN and EU sustainable development guidelines emphasise the need for more environmentally friendly energy sources in promoting further economic development. Hydrogen is one of several renewable fuels that might replace fossil fuels in a range of applications. Green hydrogen generation throughout Europe is a crucial factor in achieving this aim. According to the IEA, the use of hydrogen in the global economy increased from 18 Mt to 97 Mt per year between 1975 and 2023. The aim of the research is to determine the main advantages and obstacles of every Baltic state regarding available renewable energy resources – solar power, wind, and hydro energy; infrastructure; and industrial capacity for hydrogen utilisation within the economy. Secondary data on renewable energy from Estonia, Latvia, and Lithuania were collected and examined in accordance with the study framework. To enable a comprehensive comparison, statistical data on renewable resources, infrastructure, and industries were collected and assessed by assigning a value to each criterion evaluated. These values reflect the analysed importance of each criterion for the development of the green hydrogen industry. The statistics data for this study cover the period from 2021 to 2024. The Baltic states have an equal amount of renewable energy resources, but their distribution within each country differs significantly. Latvia has an edge in terms of hydro energy. Meanwhile, Estonia and Lithuania are leading in the area of wind and solar energy capacity development. None of the Baltic states have developed green hydrogen production for commercial purposes. However, the existing natural gas distribution network in the Baltic states could facilitate the transportation of green hydrogen.

Keywords: green hydrogen, renewables, Baltic states, hydrogen production.

Introduction

The United Nations Sustainable Development aim on energy and the European Union Green Deal objectives emphasise the importance of more environmentally friendly energy sources in promoting further economic development [1]. Hydrogen is one of several renewable fuels that might replace fossil fuels in a variety of applications. The production of green hydrogen retrieved from renewable energy (RE) sources throughout Europe is a crucial factor in achieving this aim. Moreover, the common EU hydrogen strategy [2] and national guidelines for the hydrogen sector development of 18 Member States emphasise the importance of hydrogen as a fuel for further economic growth.

The significance of green hydrogen in the energy sector can be emphasised from several angles. For example, as an energy carrier, it can be used in heat and power generation, as a feedstock in the production of synthetic fuels and other chemicals, and as a fuel for vehicles. The green hydrogen is also important in providing energy storage and grid stability when there is the need for long-term, large-volume energy storage solutions [3]. Moreover, hydrogen as an energy storage medium can provide energy solutions for remote off-grid infrastructure.

According to the International Energy Agency, the use of hydrogen in the global economy increased from 18 Mt to 97 Mt per year between 1975 and 2023. In 2023, low-carbon and green hydrogen accounted for less than 1% of the total produced amount of this fuel [4]. Meanwhile, the World Bank estimates that market demand for hydrogen will be around 600 Mt per year by 2050 [5]. In 2023, EU member states produced 10.3 Mt hydrogen [6], or 10.6% of global output. The hydrogen production capacity is crucial for faster commercialisation of this fuel and to support the entire energy transition process from fossil fuels to renewable energy sources (RES). Overall numbers regarding different RES capacity and production amount are very important in reaching the mentioned aim. [7].

The object of the study is the development of green hydrogen production in Estonia, Latvia, and Lithuania. The subject of this research is to assess the Baltic states green hydrogen production capacity based on the availability of solar, wind, and hydro energy and to explore hydrogen utilisation potential within existing industries and infrastructure. The aim of the research is to determine the main advantages and obstacles of each Baltic state regarding available RES, infrastructure, and industrial capacity for hydrogen utilisation within the economy. The importance of the study lies in an endeavour to distinguish differences and common factors within neighbouring countries with similar population and market sizes, infrastructures, and geographical conditions for concrete RE-based industry development opportunities.

Various factors must be taken into consideration in the creation of business strategies and policy initiatives in the field of green hydrogen.

Methods

According to the aim of this research, secondary statistical data on RES, electricity-generating capacity, energy balances, available hydrogen production, and transportation infrastructure in Estonia, Latvia, and Lithuania are provided. The statistical data describe the period from 2021 until 2024. The data were sourced from Eurostat, the International Energy Agency, The Wind Power database, the national statistical bureaus of the three Baltic states, as well as from publications and databases of natural gas (NG) and other infrastructure operators, energy companies and public authorities. Climate data for the countries were obtained from the Global Wind and Solar Atlases, the World Risk Report, and the climate authorities of the three Baltic nations.

To enable a detailed comparison, the collected data on RE, infrastructure, and industries is organised by assigning a value to each evaluated criterion (Table 1). The higher value (A) indicates greater importance of the specific criterion for the evolution of the green hydrogen industry [8]. Adjacent fields of industry provide limited influence on green hydrogen industry development, while directly connected fields are crucial for green hydrogen industry evolution in a particular territory.

In the research, the relative percentage difference between the countries data on criteria is expressed in the 7-point numerical scale format [9], where 1 indicates the smallest difference and 7 signifies a large disproportion among the states. It must be highlighted that econometric analyses based on a 7-point scale [10] can be applied only when the relationship between independent and dependent variables can be measured, and this will be observable when the green hydrogen industry is in the next stages of development in the Baltic states.

According to a 7-point numerical scale, the most advanced country receives a score (C) based on the criteria value (A) multiplied by the relative percentage difference, or difference coefficient, between the most and least advanced countries value (B). The second-place criteria value is determined according to the relative percentage difference between the first two higher-rated countries (1). States with inferior results in certain criteria acquired only the base value (A) of the analysed criteria. If there is no statistical data distinction between the states, or if it is equal to or less than 5%, they receive identical scores.

Table 1

Criteria and difference coefficient values for green hydrogen industry potential assessment in a certain territory

Criteria concerning the green hydrogen industry	Value (A)	Difference between countries in statistical data		Value (B)
Adjacent fields	2	No	≤ 5%	1
Directly connected fields	4	Minor	≤ 20%	2
		Average	≤ 40%	3
		Above Average	≤ 60%	4
		Major	≤ 80%	5
		Substantial	≤ 95%	6
		Huge	≤ 100%	7

$$C2 = ((A \cdot B1) - B2) \tag{1}$$

where $C2$ – second-place country rating score;
A – criteria value;
$B1$ – leading country difference coefficient;
$B2$ – second-place country difference coefficient.

For the indicators representing specific counted objects or industries, the rating score is generated by counting each object as one point, which is then multiplied by its importance value (A). The difference coefficient is not applied in this analysis.

Within the research framework regarding green hydrogen industry evaluation, 21 indicators were divided into the three categories of analysis: RES, hydrogen-suitable infrastructure, and industry linkages (Table 2). There are numerous industries linked to hydrogen utilisation, but this research only covers those with a presence in the Baltic states or with pilot projects in these sectors. As a result, the data often reflect potential developments rather than fully established industries.

Table 2

Three categories and 21 indicators for analysis for the green hydrogen industry

RES	Hydrogen-suitable infrastructure	Industry linkages
1. Renewables in electricity	12. Hydrogen fuel stations	19. Refineries
2. Wind power in electricity	13. NG network length	20. Fertiliser plants
3. Solar energy in electricity	14. NG network density	21. Hydrogen in transport
4. Hydropower in electricity	15. Major cities in gas network	
5. Wind power density	16. NG storage capacity	
6. Photovoltaic power output	17. Liquefied NG terminals	
7. Hydropower potential	18. Sea ports	
8. Wind farms capacity		
9. Solar farm capacity		
10. Hydro plant capacity		
11. Hybrid renewable parks		

Along with the research findings, major technical challenges concerning green hydrogen industry evolution are discussed (Table 3). These technical challenges are derived from current practices in EU countries and global trends, highlighting the importance of these issues for the development of the green hydrogen industry in the region. Some of the obstacles derive from the basic nature of RE utilisation, but others are rooted in specific conditions. These challenges are assessed by assigning numerical values to each issue related to the Baltic states. The value for each problem is determined using secondary statistical data, scientific publications, and evaluation reports. However, for general technical challenges related to RES, statistical data is essential in setting the numerical value. In contrast, for specific issues related to the evolution of the green hydrogen industry, publications and reports are the primary sources for establishing the numerical value, such as in the case of upgrading the NG network.

Table 3

Technical challenges for green hydrogen industry in the Baltic States

General technical challenges with RES
1. Climate change and weather extremes
2. Even distribution of RES within territory
3. Constant and balanced green hydrogen production regardless of different seasons
4. Diversity of RES near potential green hydrogen production plants
Specific challenges for green hydrogen industry evolution
5. NG network upgrade for hydrogen usage
6. Hydrogen distribution infrastructure development
7. Hydrogen storage capacity
8. Hydrogen transportation via railroad from or to Europe
9. Hydrogen liquefaction capacity
10. Potential for manufacturing of hydrogen production equipment

To assess the certain problem, a specific numerical value (C) is assigned to each challenge, based on existing practices in EU countries, emphasising the significance of these issues for the development of the green hydrogen industry. The relative percentage difference between countries' data on the criteria is presented using a 6-point numerical scale framework, where 1 indicates the smallest difference and 6 signifies the largest distinction between the countries. Subsequently, a percentage value, indicating the severeness of this problem in the particular country and its capacity to address each problem, is provided and assigned with value (D), and the final score is calculated by multiplying the value (D) with the base value (C) (Table 4).

Table 4

Values of the technical challenges and readiness of the Baltic states within the green hydrogen industry

Influence levels	Value (C)	Capacity of country to cope	Value (D)	Percentage
Minor	1	Almost none	1	≤ 10%
Average	2	Minor	2	≤ 30%
Strong	3	Below Average	3	≤ 50%
		Average	4	≤ 70%
		Above Average	5	≤ 90%
		Overall	6	≤ 100%

At the beginning, the research provides a list of important technological and geographical assumptions determining renewable hydrogen production and the overall development of the hydrogen industry within the particular area.

Results and discussion

An essential element of green hydrogen production is the availability of RE in a particular territory. The share of energy from renewable sources varies significantly among the EU Member States. According to available data in 2023, RE accounted for 24.5% of total EU energy consumption. In the last 10 years, the amount of RE used has increased by 29%. The most important renewables in 2023 in the energy balance were wind power (EU –17%, Estonia – 12%, Latvia – 4%, Lithuania – 42%), hydropower (EU – 13%, Estonia – 0.5%, Latvia – 59%, Lithuania – 7%), and solar photovoltaic (EU – 9%, Estonia – 13%, Latvia – 4%, Lithuania – 11%) [11].

RE needed for green hydrogen production should be generated near the hydrogen plants. This can be accomplished, for instance, by setting up wind or solar farms directly next to the green hydrogen facilities [12] or green hydrogen can be produced from existing water resources via hydropower plants [13]. Hydrogen storage systems are a viable solution for managing extended shutdowns of RE plants. While battery storage offers higher round-trip efficiency, it has several limitations when it comes to long-term storage [14]. When evaluating hydrogen production, it is important to consider the distance between the local production sites and the gas grid. If the hydrogen production facility is situated far from the gas grid, the hydrogen will need to be transported to the injection point [15]. The development of hydrogen infrastructure and economy are closely linked. The infrastructure scale depends on the hydrogen role in the future energy mix, while the supply chain growth may be limited by a lack of connection facilities. Prioritising the creation of green hydrogen hubs, aligned with the demand from synthetic fuels, industry, and power, is essential in the near term [16].

The Baltic states are compared in detail based on statistical data related to RE, related infrastructure, and connected industries to hydrogen utilisation. Each criterion is evaluated with a specific value, which is then summarised for further analysis (Table 5).

Table 5

Assessment of criteria for green hydrogen industry potential in the Baltic states

No	Indicators, 2023/ 2024	EST	LV	LT	A	B	EST	LV	LT
1	Wind energy, W·m^{-2}	586	445	458	4	3	12	9	9
2	Photovolt. power, kWh·day^{-1}	2.95	2.95	2.96	4	1	4	4	4
3	Hydro power pot., TWh·y^{-1}	0.1	4	2.2	4	7	4	28	24
4	3 major RE, KTOe, 2023	122.95	370.101	315.967	4	5	4	20	18
5	Hydro power, KTOe, 2023	2.236	326.264	38.71	4	7	4	28	22
6	Wind energy, KTOe, 2003	58.727	23.281	218.065	4	5	15	4	20
7	Solar power, KTOe, 2023	61.995	20.556	59.192	4	5	20	4	20
8	Solar farms cap., MW, 2023	822	500	1165	4	4	13	4	16
9	Wind farms cap., MW, 2024	457	140	1322	4	6	19	4	24
10	HES cap*., MW, 2024	135	1593	128	4	6	18	24	18
11	Hybrid RE parks, pcs	1	0	1	4	x	4	0	4
Total							**117**	**129**	**179**

Table 5 (continued)

No	Indicators, 2023/ 2024	EST	LV	LT	A	B	EST	LV	LT
12	H_2 fuel stations, pcs	0	1	0	4	x	0	4	0
13	LNG terminals, pcs	0	0	1	4	x	0	0	4
14	Sea ports and terminals, pcs	8	9	2	2	x	16	18	4
15	NG network length, km	977	1190	2288	2	4	2	4	8
16	NG network, 1 km per km^2	46.4	54.3	28.5	2	4	6	2	8
17	NG network in cities**, %	100	90	93	4	2	8	6	6
18	NG storage ***, pcs	0	1	0	4	x	0	4	0
Total							**32**	**38**	**30**
19	Refineries, pcs	0	0	1	4	x	0	0	4
20	Fertilizer plants, pcs	0	0	2	4	x	0	0	8
21	H_2 transportation****, pcs	1	1	1	4	x	4	4	4
Total							**4**	**4**	**16**
Overall score							**153**	**171**	**225**

*Kruonis Pumped Storage Plant (LT) capacity is not included as it does not operate directly as HES
**Cities with a population of ≥ 20 thousand inhabitants ***NG storages with a capacity ≥ 1 million m³
****Average amount of H_2 transport-related pilot projects and overall observations

In the next table the Baltic states are compared in terms of capacity of each state to coupe with technical challenges arising from basic characteristics of RES and specific problems for the green hydrogen industry evolution (Table 6).

Table 6

Evaluation of technical challenges with RE and green hydrogen industry in the Baltic states

No	General challenges in RES	Values per country (D)			(C)	Country score (DC)		
		ES	LV	LT		EST	LV	LT
1	Climate, weather, (WRI, 2024)*	5	4	5	2	10	8	10
2	Even distribution of RES	3	4	5	2	6	8	10
3	Constant H_2 production	3	4	4	3	9	12	12
4	Diversity of RES by H_2 plants**	4	2	4	2	8	4	8
Total						**33**	**32**	**40**
No	**Specific challenges to H_2 ind.**	**ES**	**LV**	**LT**	**(C)**	**EST**	**LV**	**LT**
5	NG network upgrade	2	1	3	3	6	3	9
6	H_2 distribution infrastructure	1	2	2	3	3	6	6
7	H_2 storage capacity	1	1	2	3	3	3	6
8	H_2 transportation via railroad	1	1	1	2	2	2	2
9	H_2 liquefaction capacity	1	1	1	2	2	2	2
10	Equipment for H_2 production	2	2	2	1	2	2	2
Total						**18**	**18**	**27**
Overall score						**51**	**50**	**67**

*World Risk Index 2024 (Institute for International Law of Peace and Armed Conflict)
**Proposed and potential H_2 plants

The evaluation of 21 criteria revealed some differences in the approach to RES among Estonia, Latvia, and Lithuania. For instance, Latvia depends on hydropower, while Estonia and Lithuania prioritise wind and solar energy. This is partly due to Latvia’s abundant hydropower potential from its rivers. At the same time, hybrid RE parks, which combine wind turbines and solar panels, are emerging as a new effort to ensure sustainable energy production throughout the year.

Regarding the infrastructure suitable for the hydrogen industry, the Baltic states are making first steps in this area. NG infrastructure can be updated and used for hydrogen transportation in terms of NG installations. Lithuania has some edge, with a more developed NG pipeline network and LNG terminal. Meanwhile, Latvia’s Inčukalns NG storage has crucial importance for NG network sustainability and balance in the region. It must be pointed out that according to the calculations framework, Lithuania received only a few points regarding its seaports, but Klaipeda port is rising as one of the leading in the Baltic Sea region and has large potential in the green hydrogen industry. At this moment, only Lithuania from the Baltic states has the potential to use hydrogen in the industry in refining and fertiliser production.

According to the analysis of technical challenges, Lithuania is better suited for green hydrogen production due to the even distribution of RES across its territory. This distribution supports balanced hydrogen production through hybrid RE plants. Approximately 85% of the land (excluding offshore capacity) has high wind power potential, and 60% is suitable for photovoltaic power for RE production sites.

Regarding the specific challenges faced by the green hydrogen industry in the region, it is crucial to emphasise the role of NG networks as a means of hydrogen transportation for users. NG pipelines must be upgraded based on the proportion of hydrogen mixed with NG to be transported. The mix proportions in the distribution system help ensure that the installed turbines, heating systems, and other technical units are not adversely affected by the presence of hydrogen. With moderate adjustments in the grid, hydrogen proportions can be increased by up to 20% [17]. Transporting hydrogen without an NG mix, however, requires more costly technological solutions. In this context, Lithuania benefits from a more modern NG network and has the potential for hydrogen transport via the pipeline from the Klaipeda port. The country's more widespread NG grids also offer the possibility of utilising hydrogen across various regions.

Conclusions

1. According to the findings of the research, the Baltic states have notable differences regarding the green hydrogen industry potential. Lithuania generates more than 2.5 times the amount of wind energy compared to Latvia and Estonia combined. In contrast, Latvia produces nearly eight times more energy from hydropower than both Lithuania and Estonia together. On the contrary, Latvia generates only 17% of the total electricity produced in the Baltic states from solar energy.
2. Although the Baltic states share similar geographical locations and weather patterns, Estonia experiences uneven distribution of RES across its territory, whereas Lithuania scores the highest in this regard. According to analyses, both countries started operating their first hybrid wind-solar power plants. The proposed green hydrogen production plants in Latvia will rely only on wind-generated electricity, resulting in an imbalanced production pattern.
3. The NG distribution network in the Baltic states could play a crucial role in transporting green hydrogen to consumers. As an initial step in incorporating green hydrogen into the energy mix of the Baltic states, hydrogen can be blended with natural gas for energy production. In this context, Lithuania has a more developed and updated NG grid compared to Latvia and Estonia.
4. With its wind and solar farm capacity, potentially well-suited industries for hydrogen utilisation, and a more advanced natural gas grid, Lithuania has the capacity to become a leading force in the development of the green hydrogen industry in the region.

Author contributions

Both authors have contributed equally to the study and preparation of this publication. Authors have read and agreed to the published version of the manuscript.

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