2023 IEEE 64th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON)

The role of hydrogen in the green future of the Baltic energy system

Antans Sauhats, Roman Petrichenko, Lubov Petrichenko,Galina Bockarjova
Institute of Power Engineering
Riga Technical University
Riga, Latvia
sauhatas@eef.rtu.lv,
romans.petricenko@rtu.lv,
lubova.petricenko@rtu.lv,
galina.bockarjova@rtu.lv

Konstantins Burcevs
AS "Augstsprieguma Tikls"
Services of the Technical Expertise Department
Riga, Latvia
konstantins.burcevs@rtu.lv

Marija Zima-Bockarjova
ABB Corporate Research Center
Switzerland
marija.zima@ch.abb.com

Abstract— **The planned and already observed increase in the use of wind and photovoltaic power plants is partially constrained by the uncontrolled variability of energy generation and consumption. The weakening of the negative influence of demand and generation variability is possible through the construction of large-scale energy storage plants (ESPs). This article is devoted to the operation and modelling of a powerful hydrogen production plant (H2PP) which can ensure a hosting opportunity for large capacity renewables in the Baltic region. An energy demand and generation balancing problem has been posed and solved. Forecasts of hydro, wind and photovoltaic generation, changes in the energy demand and market prices have been taken into consideration. An estimation of annual costs, the amount of hydrogen and the required capacity of the H2PP for energy balancing constitutes the main result of the paper.**

Keywords— energy storage; electricity market; hydrogen production; renewables; climate change mitigation.

I. INTRODUCTION

The large-scale use of renewable energy sources and power plants is an important and necessary step towards the limitation of greenhouse gas emissions into the atmosphere and climate change mitigation. Nevertheless, a further increase in the use of renewable energy sources is associated with the need to ensure the balance of generation and consumption. Consideration of intermittent generators and the unstable, poorly controlled nature of consumption amplify the problem of energy storage. This problem becomes uppermost in case of wide use of renewable energy sources and limited capacity of interconnecting power transmission lines [1]. This is just the kind of situation that is expected in the power systems of the Baltic States. This article represents an attempt to solve the above problem by creating a model of the power systems of the Baltic region, which includes an HgPP sub-model and can be used to form the operation of the power systems under market conditions. We focus on the important case of using an alkaline electrolysis system [1] for hydrogen production technology located near to a large underground reservoir. We suppose that electrolysis is green carbon-free hydrogen production from renewable resources [1].

The use of hydrogen production and storage technologies in combination with their management, taking into account the conditions of the energy market, makes it possible to balance generation and consumption and can be attractive on the basis of economic criteria. Analysis of this possibility, taking into account the specific conditions of the power systems of the Baltic region, is highly topical and forms the main contribution of this paper. The research has been implemented by creating an appropriate software tool, substantiation of which is also an important task of this paper.

A. Literature review

The authors of [1] analyse hydrogen storage from an economic point of view when compared with pumped hydro and compressed air energy systems. Their main conclusion is that hydrogen storage is more economical for large volumes of fuel. Hydrogen production has been used for a whole century. However, H2PPs which will be equipped with underground reservoirs connected to electrolysis remain in the investigation stage [1]. The large underground reservoirs of H2PPs can be used to house a renewable energy source and to ensure power balance in the power system, taking into account the medium-term (seasonal) volatility [1] of renewable generation. The authors of [2] conclude that hydrogen can be transported and utilised securely by using existing natural gas pipes, which have to be equipped with hydrogen meters and sensors. At the same time, the authors point out the difficulty of taking into account the advantages of intersessional storage of hydrogen and the impossibility of using the MARKAL platform for assessing economic suitability.

A number of research papers (a comprehensive review is performed in [2]) have concentrated on hydrogen storage problems using data for a single month. However, considering the large variation during the year, a single month cannot be set as a representative of the whole year. A more adequate study has to be performed, encompassing a whole year, with one-hour resolution.

This research is funded by the Latvian Council of Science, project SignAture, project No. lzp-2021/1-0227

2023 IEEE 64th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON) | 979-8-3503-1773-2/23/$31.00 ©2023 IEEE | DOI: 10.1109/RTUCON60080.2023.10412952

Ma et al. [3] offer an optimisation model of pumped hydro and electrochemical energy storage. The curtailment of wind and photovoltaic power is minimised. The analysis and the equations used are related to fundamental thermodynamic and electrochemical reactions that are modelled in MATLAB. Optimal scheduling of the operation of a large storage plant with a wind farm using genetic algorithms is used in [4].

Article [5] provides an estimate of the cost of hydrogen production depending on the prices of renewable electricity. Unfortunately, this information cannot be used in the electricity market when prices change every hour.

Paper [6] presents an electricity generation mix of South Australia's case study of using hydrogen for a large-scale long-term storage application targeted to support the electricity generation, which includes gas, wind, and solar energy. Battery energy storage and hybrid battery-hydrogen storage systems were compared from a techno-economic point of view. The hybrid battery-hydrogen storage system was found to be more cost-competitive with the unit cost of electricity at 0.626 $/kWh (US dollars) compared to battery-only energy storage systems with a 2.68 $/kWh unit cost of electricity. The authors remark that the generated electricity can be exported to neighbouring countries. The use of excess stored hydrogen to generate extra electricity costs can be reduced to 0.49 $.

In paper [7] it is observed that existing electrolysers can reach very good flexibility. Load changes between 10 and 90% per second can be ensured.

The research in [8]–[10] contains an economic analysis of a power system with renewable energy sources and storage plants. The HOMER tool [8] is used to optimise the system design and identify the storage capacity required. Weather data, such as wind speed, solar irradiance and air temperature, are fed into the model to estimate hourly power generation throughout the year. The energy efficiency of the electrolyser was assumed to be 70% while being capable of compressing hydrogen to 30 bar above atmospheric pressure, ready for storage. This reduced the cost of electricity to 0.626 $/kWh.

However, to our knowledge, a limited amount of studies is available in the articles considering techno-economic problems of hydrogen as a basis of large-scale energy storage in various renewable energy input scenarios, taking into account the electricity market conditions. Research on both hydrogen storage volume and costs considering the impact of renewables on electricity prices is the main objective of this paper and the methodology used is its main contribution.

B. Organisation

The rest of the article is organised as follows. Section 2 describes the object under investigation and the methodology. Section 3 is devoted to a case study of the future power systems of the Baltic States. Section 4 contains conclusions and outlines planned future work.

II. Object under Investigation and Methodology

A. The essence of the problem

The structure of the system selected for consideration is presented in Fig. 1. The mathematical model of the Baltic Power system (BPS) includes the combined power systems of the three Baltic States, namely, the Estonian, Latvian and Lithuanian power systems. The BPS has connections via transmission lines with the power systems of Finland, Sweden and Poland. The above mathematical model operates under government constraints (taxation fees for energy producers and consumers) and taking into account power market rules [11], [12].

We assume that the plant shareholders and the transmission grid operators strive to increase their profitability but are forced to follow the technical and legal constraints established by the laws of physics, the market, the government, and the networks. Wind and solar energy can be given to the network or used to accumulate energy in the hydrogen reservoir. The units of the storage power plant can be set to the generation, sleeping, or energy accumulation mode. We assume that the main task of the management of the energy system of the Baltic States is to ensure the balance of generated and consumed energy in all possible modes. The greatest (and most expensive) balancing difficulties occur during periods when renewable energy is not being generated and the capacity of interconnection lines is limited. In these cases, H2PP generation is used. The task of this article can be formulated as follows: the required volume of hydrogen production (annually, the capacity of H2PP generators and the price of generated electricity) has to be estimated [13]–[15].

Fig. 1. The diagram of the situation under consideration.

As a result of the analysis of the structure presented in Fig. 1, a decision-making methodology should be settled. To develop it, we assume that energy supply processes are governed by the day-ahead electricity market, using the structure depicted in Fig. 2.

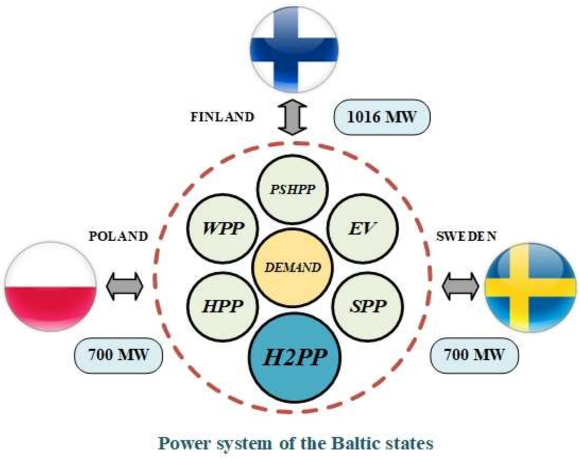

Fig. 2. Diagram of the modelled Baltic power system (BPS).

The structure represented in Fig. 2. includes the following main objects: a pumped-storage hydropower plant (PSHPP), an electrical vehicle (EV), a hydropower plant (HPP), a hydrogen production plant (H2PP), a solar power plant (SPP), and a wind power plant (WPP), electricity demand and interconnecting power lines between the Baltic States and Finland, Sweden, and Poland. We assume that all the above objects are connected to one Baltic electricity node. The capacities of the transmission lines are presented in Fig. 2 in light blue text boxes.

It is important to note that the system under review contains a balancing power plant that uses hydrogen as its energy source (see Fig. 2). We assume that hydrogen will be produced and stored in Latvia, using the reservoir/ one of the reservoirs of the existing large-scale underground gas storage (UGS). The capacity of Inčukalns UGS is 4.47 billion cubic metres, whereof 2.32 billion cubic metres of active or constantly pumped natural gas [16].

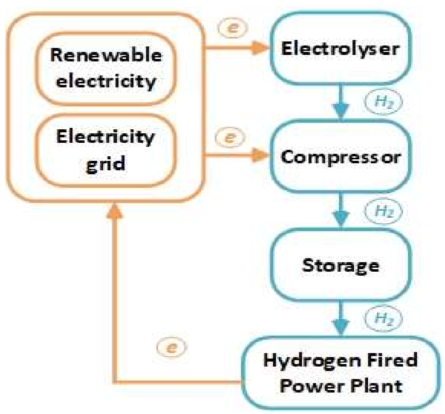

Fig. 3. The diagram of the H2PP.

We assume that the plants` shareholders strive to increase their profitability and are forced to follow the technical and legal constraints established by the rules of the Nord Pool day-ahead electricity market, the normative acts of the government and the networks [17].

Additionally, we assume that the producers depicted in Fig. 2 do not influence the day-ahead prices of the global electricity market and do not participate in the ancillary services of the system. We suppose that H2PPs will play the role of backup stations, whose main task is generation of electricity in the case when the available capacity of the remaining power plants cannot ensure power balance in the Baltic States.

B. *The statement of the control optimisation problem*

The decision-making methodology can be created on the basis of formulating and solving the optimal control problem for the interconnected power systems depicted in Fig. 2. In addition, the rules of the electricity market must be taken into account.

The balance of the power system generation/demand and supply for the day-ahead market is formed by formulating and solving the problem of optimising the expenses/incomes of all the participants. To simplify this problem, the following additional postulates have been assumed:

- The market proposals of all the market participants are formed on the basis of the assumption that the hourly energy prices are known (in the form of hourly price forecasts);
- The modes of the Baltic power systems do not impact the electricity prices in neighbouring countries;
- The energy prices of the Baltic States may differ from the forecast ones since they are determined in accordance with the market rules, taking into account not only the proposal but also the import/export possibilities and constraints as well as the prices of the neighbouring countries;
- The internal constraints of the Baltic States transmission network are complied with in all modes. In this case, the Baltic network is reduced to one node (see Fig. 2);
- The power systems of the neighbouring countries are capable of fully loading the interconnections when exporting or importing electricity;

The above postulates ensure dramatic simplification of the long-term development planning problem since: detailed models of the power systems of the neighbouring countries are not used; the expenses/incomes of each participant, given set future prices, depend only on their own actions. The problem of selecting modes for power plants disintegrates into a number of much simpler sub-problems. To solve them, medium-term mode planning models and tools can be used, which are substantiated and described in our earlier studies [18]–[23].

It is important to note that the task to be solved requires a description of the system for the entire planning period, which makes it necessary to forecast the parameters of the influencing processes [24]. Fortunately, methods presented in scientific publications [25] can be used when predicting processes, selecting and implementing the optimisation procedure, the complexity of which can be reduced by decomposing the planning horizon into a set of smaller sub-horizons [26], for example, a one-week-long one. The scenario method [27] will be exploited for the study of the objects to be analysed. With the help of this method, the expected energy generation, demand and prices will be described. The models of all the system elements (see Fig. 2) can serve as the basis for the problems to be solved. In this study, models described in our previous articles [14], [18], [20], [28]–[33] are employed. In addition, as shown in Fig. 3, a simplified model of hydrogen production, storage and transformation into electricity can be used.

The simplest model can be used to describe the structure given in Fig. 3:

$$W_{HG} = W_G/K_1$$
$$W_{FH} = W_{HG}/K_2\text{'} \quad (1)$$

where: W_G — the electricity amount consumed from the grid for hydrogen production (MWh); W_{HG} – produced hydrogen energy (MWh); W_{FH} — electricity generated by firing hydrogen (MWh), K_1,K_2 — efficiencies.

C. Estimation of the hydrogen amount

The structure of the hydrogen impact assessment algorithm is given in Fig. 4. The contents of the first block of the algorithm, namely, forecasting of the influencing processes and optimisation of power plants, are widely described in the scientific literature [11], [14], [18], [20], [28]. The second block performs an electricity supply proposal to the market that takes place by using the results of the optimisation of each generator's operation. Examples of optimal operation of individual generators can be found in many publications [3], [4], among them in our earlier articles [34], [35]. We suppose that energy demand is inflexible and demand is forecasted for every hour. The supply and demand curves form the basis for the market operator's decision regarding the selection of specific generators and their capacities for each hour of the planning period.

Below, we will look at the last three blocks of the algorithm under review. We will take into account the impact of the energy systems of neighbouring countries by replacing them:

- with one generator *Gp* (see Fig. 5), the capacity of which makes it possible to fully ensure the interconnection transmission capacity for export;
- with a single combined load *Lp* with a maximum capacity equal to the interconnection transmission capacity for imports.

The task of the electricity market operator is to choose generator capacities in each hour of the planning period, which ensures:

- capacity balance;
- the lowest energy supply (generation or consumption) costs throughout the planning period.

$$\sum_{t=1}^{T}(\sum_{i=1}^{n} WBS_{t,i} \cdot Pr_{t,i} + Wp_{t,i} \cdot \mathrm{Pr}p_{t,i}) \to min, \quad (2)$$

$$\sum_{i=1}^{n} WBS_{t,i} + Wp_{t,i} = LBS_t + Lp_t; t=1,\ldots,8760 \quad (3)$$

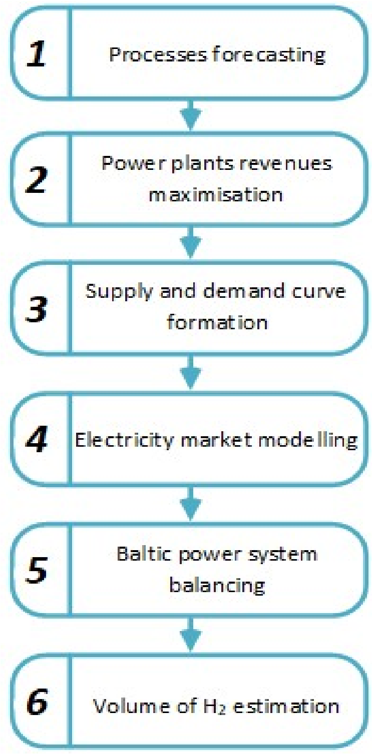

Fig. 4. The flowchart of H2 volume estimation algorithm.

where $WBS_{t,i}$ - energy produced or consumed by Baltic states generators in each time *t* (MWh), *i* – separate generator or consumer; T – time horizon (8760 hours); n – the number of generators and consumers; $Pr_{t,i}$ - price of electricity bidden by the generator or consumer *i* to the market in time t (EUR/MWh); $Wp_{t,i}$, $Prp_{t,i}$ - energy and price of energy supplied or consumed by partners from Poland, Sweden and Finland to the Baltic. Let's note that the generated energy should be taken into account with a plus sign, and the consumed energy with a minus sign.

The equation (3) must be fulfilled for all $t \subset T$.

We omit many other constraints to be described along with (3) since their detailed description can be found in the literature [18], [21], [32], [34], [35].

The complexity of the problem (2) strongly depends on a number of factors:

- the length of the planning period and the composition of market players. Our paper analyses long-term energy storage, which requires choosing a planning period that covers seasonal fluctuations (a year and more is needed);
- on the objective function and the constraint description type. The minimisation task is greatly simplified if linear expressions are used;
- the length of time period t; in our case, there may be short-term storage systems agreed upon between market participants, the analysis of which requires taking into account hourly changes;

- the composition and type of unknown quantities. The power of the electrolyser and the volume of the reservoir are considered as optimisation variables in the current task. Energy prices depend on these quantities, so (2) contains multiplication of unknown variables, which makes it impossible to directly use linear programming.

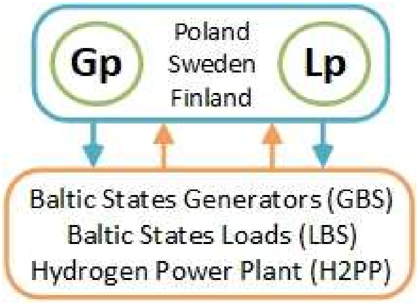

Fig. 5. Electricity market modelling.

We will assume that the price of energy produced by a hydrogen power plant is higher than the cost of energy produced by any of the other plants. Thus, generation from hydrogen is possible only in those hours when the active power balance of energy systems can be provided only with the help of hydrogen. In addition, we assume that the volume of the hydrogen storage reservoir is large enough to ensure the balance of the energy systems at any hour of the planning period, regardless of the reservoir's usage schedule in the past or in the future. This assumption corresponds to the case of using a reservoir with an infinite volume. Finally, we assume that the capacities of hydrogen plants and electrolysers are not limited in the first step of algorithm execution. The assumptions made allow dramatically simplifying the optimisation problem and ensuring the use of linear programming for solving it. Indeed, task (2) can be divided into two parts:

- Selection of generation schedules. Given that all generator bids to the market are known, task (2) can be replaced by a simpler set of tasks for $t \subset T$, where T equals to 8760 (hours in the year):

$$\begin{gathered} \sum_i (WBS_{1,i} \cdot Pr_{1,i} + Wp_{1,i} \cdot \mathrm{Prp}_{1,i}) \to min \\ \dots\dots\dots\dots\dots\dots\dots\dots \\ \sum_i (WBS_{8760,i} \cdot Pr_{8760,i} + Wp_{8760,i} \cdot \mathrm{Prp}_{8760,i}) \to min \end{gathered} \quad (4)$$

As a result of the implementation of procedures (4), the amount of energy produced by a H2PP is estimated. This gives an opportunity to estimate the amount of H2 used from the reservoir and the amount of hydrogen required. The amount of H2 required for balancing provides an opportunity to solve the task of minimizing the cost of energy used for its production.

To do this, it is necessary to return to the expression (2) and perform minimisation, taking into account additional restriction, which is described by the following requirement: balancing energy must be equal to energy which has been spent for faired gas production.

III. CASE STUDY

A. Scenario description

In the Table I we present four specific scenarios which characterise the years 2030, 2040 and 2050. The maximum value of the total power consumption, total generation and capacity of each kind of power plant over one year is depicted. The year 2050 is presented in two scenarios; S3 includes a modest forecast for the capacity of renewable energy resources, while S4 represents a more rapid version of their development.

TABLE I. BASIC PARAMETERS OF BALTIC FUTURE SCENARIO

Demand	SPP	WPP	HPP	PSHPP
Scenario 'S1' for 2030 year				
6 026 [a] 37,86 [b]	1 400[a] 1.63 [b]	3 900 [a] 11.64[b]	1 562 [a] 1,90 [b]	1 625 [a] 2,85 [b]
Scenario 'S2' for 2040 year				
6 629 [a] 39,83 [b]	1 600 [a] 1,87 [b]	5 000 [a] 14,92 [b]	1 562 [a] 1,90 [b]	1 625 [a] 2,85 [b]
Scenario 'S3' for 2050 year				
7 233 [a] 41,80 [b]	2 400 [a] 2,80 [b]	7 000 [a] 20,88 [b]	1 562 [a] 1,90 [b]	1 625 [a] 2,85 [b]
Scenario 'S4' for 2050 year				
7 233 [a] 41,80 [b]	3 900 [a] 4,55 [b]	12 000 [a] 35,80 [b]	1 562 [a] 1,90 [b]	1 625 [a] 2,85 [b]

a. maximal consumption / maximal generation, MWh/h

b. Annual power demand / annual power supply, TWh

The following parameters of the hydrogen system are used:

Efficiency K1 of electrolyser (1) — 0.7.

Efficiency K2 of H2PP ((1) — 0.6.

Capacity of hydrogen storage reservoir — 2.3 Mm^3.

Density of hydrogen — 0.0897 kg/m^3.

Thermal capacity of hydrogen — 33.2 kWh/m^3.

The loses in the converting process of 1 MWh electricity into hydrogen energy storage and its further combustion to generate electricity are shown in Fig. 6.

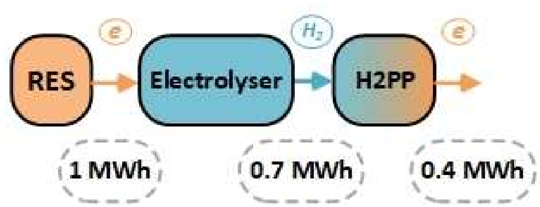

Fig. 6. The diagram of the H2PP.

B. Forecasting of market prices and solar generation

A naïve approach [36] and the prices of 2018 (to remove the consequences of the Covid epidemic, new data were omitted) were used.

To predict the production of wind and solar energy, we use the well-known approach [37] based on the lagging time series of production records of neighbouring photovoltaic plants. For this purpose, during 2018, data were collected from records [38] about the generation of 20 randomly selected distributed PV plants and total capacity of wind plants. [39]

C. Implementation of the maximisation procedure

Despite the need for multiple use of the maximisation procedure, the possibility of using linear programming allows us solving the problem of optimisation and distributing additional profit for an acceptable period of time. For the above optimisation purpose, MATLAB 2022b, more specifically, the linear programming optimisation function — "linprog" — was applied. [14], [18], [29], [32], [40], [41]

D. Nodelling results

The main results are reflected in Table II.

TABLE II. MAIN RESULTS

Energy deficit			**Hydrogen Power Plant**	
Total, TWh/y	***Frequency of occurrence, %***	***Hour peak, MWh/h***	***Total, Mm^3/y***	***Hour peak, Mm^3/h***
Scenario 'S1' for 2030 year				
3.037	38.85%	2 740	1 019.00	8.22
Scenario 'S2' for 2040 year				
3.572	36.97%	3 313	1 190.66	9.94
Scenario 'S3' for 2050 year				
3.620	31.14%	3 865	1 206.66	11.59
Scenario 'S4' for 2050 year				
1.978	18.71%	3 746	659.33	11.24

The results shown in the table enable the conclusion that the conversion of the power systems of the Baltic States to the use of hydrogen will require up to 11.59 million cubic meters of hydrogen. A power plant capacity of 3,865 MW will be required. Let us note that the scale of the existing gas storage in Latvia [42] is estimated just in billions of cubic meters and thereby ensures the needed size of the storage reservoir. Assuming that the price of electricity produced from hydrogen is 0.626 \$/kWh [6], we can estimate its costs ($CH2_{year}$), for example, for whole year of scenario S3 (2050 year) (equation (5)) and its peak hour (equation (6)) of energy deficit ($CH2_{ph}$):

$$CH2_{year} = WBS_{S3} \cdot \mathrm{Pr} = 3.620 TWh \cdot 0.626 \cdot 10^9 = 2.266\ billion\ \$ \quad (5)$$

$$CH2_{ph} = WBS_{S3} \cdot \mathrm{Pr} = 3\,865 MWh \cdot 0.626 \cdot 10^3 = 2.419\ million\ \$ \quad (6)$$

It is easy to see that the cost of hydrogen electricity can be about half of the cost of energy produced by all other power plants. Fig. 7 contains dependency curves between hydrogen price on global market and capital investments for supporting BPS balance.

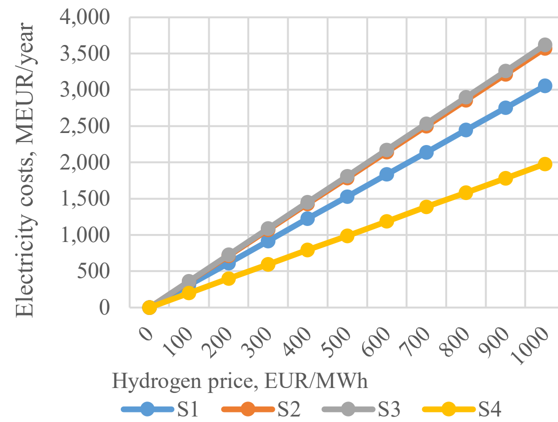

Fig. 7. The impact of hydrogen price on the BPS balancing service.

IV. CONCLUSIONS

The cost of hydrogen energy can be estimated by choosing the operating mode of all the power plants of a power system on the basis of the formulation and solution of an optimisation problem that requires prediction of the processes of price changes and wind and solar generation and take into account electricity market rules.

The use of integer linear programming provides an acceptable amount of time to search for the optimal power system operation solution.

Hydrogen production and storage is feasible in Latvia. Such a course of action would allow ensuring the balance of energy production and consumption, using large amounts of renewable resources.

REFERENCES

[1] M. Abdellatif, M. Hashemi, and S. Azizmohammadi, "Large-scale underground hydrogen storage: Integrated modeling of reservoir-wellbore system," *Int J Hydrogen Energy*, vol. 48, no. 50, pp. 19160–19171, Jun. 2023, doi: 10.1016/J.IJHYDENE.2023.01.227.

[2] P. E. Dodds and S. Demoullin, "Conversion of the UK gas system to transport hydrogen," *Int J Hydrogen Energy*, vol. 38, no. 18, pp. 7189–7200, Jun. 2013, doi: 10.1016/J.IJHYDENE.2013.03.070.

[3] X. Ma *et al.*, "Optimizing pumped storage hydropower for multiple grid services," *J Energy Storage*, vol. 51, p. 104440, Jul. 2022, doi: 10.1016/J.EST.2022.104440.

[4] B. Panagiotis and K. Katsifarakis, "Optimizing operation of a large-scale pumped storage hydropower system coordinated with wind farm by means of genetic algorithms," *GlobalNEST International Journal*, vol. 21, pp. 1–6, Feb. 2019, doi: 10.30955/gnj.002978.

[5] Lazard, "Lazard's Levelized Cost of Hydrogen Analysis-Executive Summary Overview of Analysis," 2021, [Online]. Available: https://www.lazard.com/media/erzb5rkv/lazards-levelized-cost-of-hydrogen-analysis-version-20-vf.pdf

[6] S. Kharel and B. Shabani, "Hydrogen as a Long-Term Large-Scale Energy Storage Solution to Support Renewables," 2018, doi: 10.3390/en11102825.

[7] H. Lange, A. Klose, W. Lippmann, and L. Urbas, "Technical evaluation of the flexibility of water electrolysis systems to increase energy flexibility: A review," *Int J Hydrogen Energy*, vol. 48, no. 42, pp. 15771–15783, May 2023, doi: 10.1016/J.IJHYDENE.2023.01.044.

[8] S. Kharel and B. Shabani, "Hydrogen as a long-term large-scale energy storage solution to support renewables," *Energies (Basel)*, vol. 11, no. 10, 2018, doi: 10.3390/en11102825.

[9] J. Assaf and B. Shabani, "Economic analysis and assessment of a standalone solar-hydrogen combined heat and power system integrated with solar-thermal collectors," *Int J Hydrogen Energy*, vol. 41, Sep. 2016, doi: 10.1016/j.ijhydene.2016.08.117.

[10] O. Guerra, J. Zhang, J. Eichman, P. Denholm, J. Kurtz, and B.-M. Hodge, "The Value of Seasonal Energy Storage Technologies for the Integration of Wind and Solar Power," *Energy Environ Sci*, vol. 13, May 2020, doi: 10.1039/D0EE00771D.

[11] K. Baltputnis and Z. Broka, "Estimating the Benefit from Independent Aggregation in the Day-Ahead Market," *Latvian Journal of Physics and Technical Sciences*, vol. 58, pp. 32–46, Jun. 2021, doi: 10.2478/lpts-2021-0015.

[12] Z. Broka and K. Baltputnis, "Open-source electricity market modelling for the Baltic states: Review and requirements," *International Conference on the European Energy Market, EEM*, vol. 2023-June, 2023, doi: 10.1109/EEM58374.2023.10161953.

[13] A. Sauhats, Z. Broka, and K. Baltputnis, "Energy transition of the Baltic states: Problems and solutions," *Latvian Journal of Physics and Technical Sciences*, vol. 58, no. 3, pp. 3–14, Jun. 2021, doi: 10.2478/lpts-2021-0013.

[14] L. Petrichenko, R. Petrichenko, A. Sauhats, K. Baltputnis, and Z. Broka, "Modelling the Future of the Baltic Energy Systems: A Green Scenario," *Latvian Journal of Physics and Technical Sciences*, vol. 58, no. 3, pp. 47–65, 2021, doi: 10.2478/lpts-2021-0016.

[15] K. Baltputnis and Z. Broka, "Future scenarios of the Baltic power system with large penetration of renewables," *International Conference on the European Energy Market, EEM*, vol. 2023-June, 2023, doi: 10.1109/EEM58374.2023.10161795.

[16] "Information about the storage | Conexus." Accessed: Jun. 26, 2023. [Online]. Available: https://www.conexus.lv/information-about-storage

[17] [17]Day-ahead trading, "Nord Pool day-ahead market." [Online]. Available: https://www.nordpoolgroup.com/en/trading/Day-ahead-trading/

[18] . Sauhats, R. Petrichenko, K. Baltputnis, Z. Broka, and R. Varfolomejeva, *A multi-objective stochastic approach to hydroelectric power generation scheduling*. 2016. doi: 10.1109/PSCC.2016.7540821.

[19] A. Sauhats, H. H. Coban, K. Baltputnis, Z. Broka, R. Petrichenko, and R. Varfolomejeva, "Optimal investment and operational planning of a storage power plant," *Int J Hydrogen Energy*, vol. 41, no. 29, pp. 12443–12453, Aug. 2016, doi: 10.1016/J.IJHYDENE.2016.03.078.

[20] R. Petrichenko, L. Petrichenko, K. Baltputnis, A. Sauhats, S. Gudzius, and A. Slivikas, "Selection of the initial state and duration of the planning period in the tasks of managing energy storage systems," *2020 IEEE 61st Annual International Scientific Conference on Power and Electrical Engineering of Riga Technical University, RTUCON 2020 - Proceedings*, no. 1, pp. 18–23, 2020, doi: 10.1109/RTUCON51174.2020.9316613.

[21] A. Sauhats, R. Petrichenko, Z. Broka, K. Baltputnis, and D. Sobolevskis, "ANN-based forecasting of hydropower reservoir inflow," *2016 57th International Scientific Conference on Power and Electrical Engineering of Riga Technical University, RTUCON 2016*, pp. 2–7, 2016, doi: 10.1109/RTUCON.2016.7763129.

[22] K. Baltputnis, R. Petrichenko, and D. Sobolevsky, *Heating Demand Forecasting with Multiple Regression: Model Setup and Case Study*. 2018. doi: 10.1109/AIEEE.2018.8592144.

[23] K. Baltputnis, Z. Broka, A. Silis, G. Cingels, and G. Junghans, "Efficient market-based storage management strategy for FCR provider with limited energy reservoir," *International Conference on the European Energy Market, EEM*, vol. 2023-June, 2023, doi: 10.1109/EEM58374.2023.10161770.

[24] Balyberdin Viktor and Sveggen Kurt, "SKM Market Predictor AS - Long-Term Power Outlook." Accessed: Jun. 08, 2023. [Online]. Available: https://www.skmenergy.com/reports/long-term-power-outlook

[25] A. Sauhats, L. Zemite, L. Petrichenko, I. Moshkin, and A. Jasevics, "A estimating the economic impacts of net metering schemes for residential PV systems with profiling of power demand, generation, and market prices," *Energies (Basel)*, vol. 11, no. 11, Nov. 2018, doi: 10.3390/en11113222.

[26] Lloyd S. and Shapley A., "Value for n-person Games," in *Contributions to the Theory of Games, Volume II*, vol. 28, H.W. Kuhn and A.W. Tucker, Eds., Annals of Mathematical Studies v. 28, pp. 307–317.

[27] F. Adam and P. Humphreys, "Encyclopedia of Decision Support Technologies," vol. II, p. 1064, 2008, Accessed: Jun. 19, 2023. [Online]. Available: http://www.lavoisier.fr/livre/notice.asp?id=RA6W6OAKSK2OWR%0A papers3://publication/uuid/976A428B-F10F-4169-87F9-6FD56AECF4FA

[28] R. Petrichenko, J. Kozadajevs, L. Petrichenko, and A. Silis, "Reserve power estimation according to the Baltic power system 2050 development plan," in *ENERGYCON 2022 - 2022 IEEE 7th International Energy Conference, Proceedings*, Institute of Electrical and Electronics Engineers Inc., 2022. doi: 10.1109/ENERGYCON53164.2022.9830517.

[29] R. Petrichenko, J. Kozadajevs, L. Petrichenko, and A. Silis, "Reserve power estimation according to the Baltic power system 2050 development plan," *ENERGYCON 2022 - 2022 IEEE 7th International Energy Conference, Proceedings*, 2022, doi: 10.1109/ENERGYCON53164.2022.9830517.

[30] A. Sauhats, R. Petrichenko, L. Petrichenko, A. Silis, and R. Komarovs, "The assessment of the impact of electric vehicles on the power balance of the Baltic energy system," *2021 IEEE 62nd International Scientific Conference on Power and Electrical Engineering of Riga Technical University, RTUCON 2021 - Proceedings*, pp. 10–14, 2021, doi: 10.1109/RTUCON53541.2021.9711587.

[31] R. Petrichenko, L. Petrichenko, O. Ozgonenel, and R. Komarovs, "The assessment of long-term import-export capabilities of Baltic power system," *2021 IEEE 62nd International Scientific Conference on Power and Electrical Engineering of Riga Technical University, RTUCON 2021 - Proceedings*, no. 1, 2021, doi: 10.1109/RTUCON53541.2021.9711721.

[32] R. Petrichenko, L. Petrichenko, A. Sauhats, A. Slivikas, S. Gudzius, and M. Zima-Bockarjova, "Profitability Study of Floating PV and Storage Pumped Hydropower Plant," *International Conference on the European Energy Market, EEM*, vol. 2020-Septe, no. 1, pp. 1–6, 2020, doi: 10.1109/EEM49802.2020.9221983.

[33] R. Petrichenko, L. Petrichenko, K. Baltputnis, A. Sauhats, S. Gudzius, and A. Slivikas, "Selection of the initial state and duration of the planning period in the tasks of managing energy storage systems," *2020 IEEE 61st Annual International Scientific Conference on Power and Electrical Engineering of Riga Technical University, RTUCON 2020 - Proceedings*, no. 1, 2020, doi: 10.1109/RTUCON51174.2020.9316613.

[34] L. Petrichenko, Z. Broka, A. Sauhats, and D. Bezrukovs, "Cost-benefit analysis of li-ion batteries in a distribution network," *International Conference on the European Energy Market, EEM*, vol. 2018-June, no. 1, 2018, doi: 10.1109/EEM.2018.8469782.

[35] [35]M. Zima-Bockarjova, A. Sauhats, L. Petrichenko, and R. Pertichenko, "Shapley-Value-Based Charging and Discharging Scheduling for Electric Vehicles in a Parking Station," *2019 IEEE 60th Annual International Scientific Conference on Power and Electrical Engineering of Riga Technical University, RTUCON 2019 - Proceedings*, pp. 1–21, 2019, doi: 10.1109/RTUCON48111.2019.8982376.

[36] Techleens, "Naive Approach Definition and Explanation." [Online]. Available: https://techleens.com/mba/scm/what-is-naive-approach.php

[37] J. Antonanzas, N. Osorio, R. Escobar, R. Urraca, F. J. Martinez-de-Pison, and F. Antonanzas-Torres, "Review of photovoltaic power forecasting," *Solar Energy*, vol. 136, pp. 78–111, Oct. 2016, doi: 10.1016/J.SOLENER.2016.06.069.

[38] SolarEdge, "SolarEdge database." [Online]. Available: https://monitoringpublic.solaredge.com/solaredge-web/p/home/public?locale=en_US

[39] "ENTSO-E Transparency Platform." Accessed: Jun. 26, 2023. [Online]. Available: https://transparency.entsoe.eu/dashboard/show

[40] Help Center (MathWorks), “linprog - solve linear programming problems,” Available online: [Online]. Available: https://www.mathworks.com/help/optim/ug/linprog.html

[41] R. Petrichenko, K. Baltputnis, D. Sobolevsky, and A. Sauhats, “Estimating the costs of operating reserve provision by poundage hydroelectric power plants,” *International Conference on the European Energy Market, EEM*, vol. 2018-June, no. 1, pp. 4–8, 2018, doi: 10.1109/EEM.2018.8469876.

[42] CONEXUS, “Information about the storage | Conexus.” Accessed: Jun. 08, 2023. [Online]. Available: https://www.conexus.lv/information-about-storage

[43]