Selection of the initial state and duration of the planning period in the tasks of managing energy storage systems

Roman Petrichenko, Lubov Petrichenko, Karlis Baltputnis, Antans Sauhats
Institute of Power Engineering
Riga Technical University
Riga, Latvia
romans.petricenko@rtu.lv, lubova.petricenko@rtu.lv, karlis.baltputnis@rtu.lv, sauhatas@eef.rtu

Saulius Gudzius, Aivaras Slivikas
Department of Electrical Power Systems
Kaunas University of Technology
Kaunas, Lithuania
saulius.gudzius@ktu.lt, aivaras.slivikas@ktu.edu.lt

Abstract— The large-scale use of renewable energy sources and combined heat and power plants and the unstable, poorly controlled nature of consumption aggravate the problem of energy storage. When designing and operating storage plants, the task is to ensure their profitability. Usually optimization tasks are formulated with the goal of maximizing profits. When solving these problems, significant difficulties may arise, since in the general case they are nonlinear, stochastic, multistage and contain a large number of decision and state variables. This article is devoted to the problem of ensuring acceptable accuracy and time spent on maximizing profits of pumped storage hydropower plants. Based on an analysis based on the data from a real power plant, Nord Pool electricity price records and mixed integer linear programming, the dependence of the optimisation results on the initial state of the reservoirs and the duration of the planning period is shown. The results can be used both when controlling real stations and at the stage of their feasibility study.

Keywords— renewable energy; pumped storage hydropower plant; floating photovoltaic plant; optimisation

I. INTRODUCTION

The large-scale use of renewable energy sources [1-3] and combined heat and power plants (CHPP) is an important and necessary step towards limiting greenhouse gas emissions into the atmosphere and mitigating the climate change. Nevertheless, a further increase in the use of these energy sources is associated with the need to solve the complex task of ensuring balance of generation and consumption. Intermittent generators and the unstable, poorly controlled nature of consumption aggravate the problem of energy storage [4-7]. Energy storage technologies have to integrate rapidly developing intermittent energy sources like wind and solar in the power system. Various technologies of storage plants (SP) are intensively researched and already used: pumped storage hydropower plants (PSHP), rechargeable batteries, electrical vehicles, hydrogen storage, compressed air energy storage, reservoir and poundage hydropower plants etc. [8, 9]. When designing and operating a storage plant, the task is to ensure their profitability. Usually, optimization tasks are formulated with the goal of maximizing profits, which depends on volatile prices in the electricity markets.

There are numerous approaches in scientific literature to solving the task of storage plant scheduling optimization.

For instance, the authors of [10] deal with the problem of devising optimal bidding strategy for a multi-unit pumped storage plant. They propose a solution employing evolutionary tristate particle swarm optimization. The same authors have also proposed a multi-looping sequential optimization approach using mixed integer programming [11]. A number of scientific publications investigate optimal scheduling models of SP operation [12-14]. The existing literature on solving pumped hydropower storage scheduling problems can be divided into three time categories: short, medium and long-term planning. In [15], the authors formulate the optimization task as a mixed integer problem. They use a multi-stage looping optimization intraday algorithm for SP, considering e.g. reservoir limits, quarter-hourly prices, grid charges and machine availabilities. The algorithm has been tested in a real-life application. In [16], the SP production planning problem is also modelled by mixed integer linear programming, taking into account the spot and frequency markets. Short-term scheduling of the SP is resolved by a heuristic method in [13] and by the linear programming method in [17]. Medium-term planning (one week) of SP operation is discussed in [18]. The authors use an optimization model based on genetic algorithms (an evolutionary algorithm). A model was proposed for the coordinated operation optimization on a weekly horizon for a hydroelectric development including a large hydropower plant and a large SP. Long-term (one year) planning optimization of SP operation is presented in [19]. A fast maximisation algorithm using dynamic programming [20], taking into account all the technical assumptions and operational restrictions, is proposed. A model for optimizing the operation of a hybrid PV power plant. The aim of this paper is to present a model for the optimal operation of PV-PSHPP to minimize the operation cost and the cost of PV energy curtailment.

Summing up the publications on various types of SP, we can note:

This work has been supported by the European Regional Development Fund within the Activity 1.1.1.2 “Post-doctoral Research Aid” of the Specific Aid Objective 1.1.1 “To increase the research and innovative capacity of scientific institutions of Latvia and the ability to attract external financing, investing in human resources and infrastructure” of the Operational Program “Growth and Employment” (No. 1.1.1.2/VIAA/1/16/021 and No. 1.1.1.2/VIAA/2/18/317).

- The existence of a large number of models and algorithms for optimal control of the process of energy storage and generation.
- The complexity of the optimization problem, since, in the general case, they are non-linear, stochastic, multi-stage and contain a large number of decision and state variables.
- The need for ensuring acceptable accuracy and calculation time. The essence of this problem is easily explained by the type of the objective function, which can be written as:

$$C^{T_{pl}*} = \boldsymbol{E}(\boldsymbol{F}(P_{pr}^t, W^t, W_G^t, W_C^t, T_{pl}, So)) \to \max \tag{1}$$

where $C^{T_{pl}*}$ stands for the mathematical expectation of SP profit obtained during the planning period T_{pl} ; F — the profit estimation procedure; $P_{pr}^t, W^t, W_G^t, W_C^t$ — multidimensional process changing in time: P_{pr}^t stands for the energy market prices; W^t is the amount of electricity generated by PV technology; W_G^t is the amount of electricity generated by SP; W_C^t stand for the energy amount consumed by SP; So - reservoir levels at the beginning and the end of the planning period.

$W_G^t, W_C^t,$ should be considered as decision variables. W^t *and* P_{pr}^t are state variables; various methods of prediction [21] are used to set these variables, which are most often combined with the scenario approach [22]. Note that the number of decision variables can be quite significant. Maximization procedure (1) must be implemented taking into account many technical, economic and environmental limitations [23, 24]. Typically, the synthesis and application of procedure (1) is based on prediction and modelling of the processes of change during the planning horizon: electricity prices; energy generated by SP; energy consumed by the SP, revenues and expenses of the plant, control actions that set the operation mode of the plant and the network. Based on the use of the appropriate maximization procedure, a search is carried out for control actions that establish the operation mode of the SP. Expression (1) can be reduced to the form:

$$C^{T_{pl^*}} = \frac{1}{N} \cdot \sum_{n=1}^{N} \sum_{t=1}^{T_{pl}} F(P_{pr}^t, W^t, W_G^t, W_C^t, T_{pl}, So) \tag{2}$$

Where N is number of scenario. To generate scenario, you can use one of the known methods [25].

Despite the widespread use of procedures of the form (2), the issue of a reasonable choice of the duration of the planning period and the initial state of the SP remains unsolved. This article presents an attempt to fill this gap.

The case study presented below is based on the example of a real, large-scale SP, using its technical parameters, as well as the parameters of an additional large-scale floating solar plant with photovoltaic technology (FPV), which can be placed in the reservoir of a pumped storage hydropower plant (PSHP). We consider only one storage power plant operational strategy – a stand-alone storage plant benefiting solely from price differences in the day-ahead market (i.e. price arbitrage). The PSHP in question is not intended for long-term storage of energy and benefiting from seasonal price variances. Rather it exploits the short to medium-term price spread.

The remaining part of the paper is organised as follows: Section II contains the case study and results. In this section, the description of the object under study is provided. Additionally, the objective function and constraints are also described. Finally, this section deals with the research topic of this paper, namely, determination of the optimal initial water head level striving to maximize the benefit from an FPV-PSHPP system. Section III summarizes the key conclusions of the paper.

II. Case study and results

A. Object under study

The large-scale PSHP currently existing in Lithuania [26], which is supposed to be supplemented by an FPV [27] plant is selected as the object under study. Parameters of the FPV-PSHP system are presented in Table I. We assume that the hypothetical combined plant is a participant of the Nord Pool day-ahead electricity market.

TABLE I. FPV-PSHP plant parameters

Parameter, Unit of measurement	**Value**
Upper reservoir area, km^2	3.05
Maximum water head, m	113.5
Minimum water head, m	105.0
Number of reversible pump-turbine units, pcs	4
Rated unit capacity in generation mode, MW	225.0
Rated unit capacity in pumping mode, MW	220.0
Efficiency in generation/ pumping mode, %	90.0 / 80.0
Rated capacity of FPV, MW	250
Total reservoir volume, m^3	48,000,000

When planning the operation, we assume that the pump-turbine units at each hour can work only with rated power and that simultaneous operation in both the generation mode and the pumping mode is impossible. The use of solar energy is completely dependent on the mode of the PSHP: if this plant is operating in a generator or in an idle state, then the solar energy is transferred to the grid; if pumping mode is selected, then solar energy is used on site, reducing energy consumption from the grid. Rated FPV capacity (250 MW) corresponds to the area of the upper reservoir (3,000,000 m^2).

B. Objective functions and constraints

For ease of reading, we present the objective function (3) with only one pump-turbine unit. In the case of several units and scenarios, two additional summation operators are included; the number of decision (Boolean) variables increases in proportion to the number of units, however, these changes do not cause fundamental complications. Given the assumptions made, the task of maximizing the income of the FPV-PSHP ($I_{FPV-PSHP}^*$) can be written in the following form:

$$I^{*}_{FPV-PSHP} = \sum_{t=1}^{T_{pl}} P^{t}_{gen} \cdot \tau \cdot \eta_{gen} \cdot (P^{t}_{r\ mark}) \cdot \beta^{t}_{gen}$$
$$+ P^{t}_{FPV} \cdot \tau \cdot (P^{t}_{r\ mark}) \cdot \beta^{t}_{FPV,g} - P^{t}_{pump} \cdot \tau \cdot \frac{1}{\eta_{pump}} \qquad (3)$$
$$\cdot (P^{t}_{r\ mark} + P_{tran}) \ \cdot \beta^{t}_{pump}$$
$$+ P^{t}_{FPV} \cdot \tau \cdot (P^{t}_{r\ mark} + P_{tran}) \cdot \beta^{t}_{FPV,p} \rightarrow max$$

where P^{t}_{gen} — the unit's operational range in generator mode at the *t*-th hour, MW; τ — sampling step (one hour); η_{gen} — efficiency coefficient in generator mode; β^{t}_{gen} — Boolean (decision) variable (1 — in generator mode); P^{t}_{FPV} — amount of generated energy from FPV at the *t*-th hour, MW; $\beta^{t}_{FPV,g}$ — Boolean (decision) variable (1 — in case of selling energy to the grid); P^{t}_{pump} —the unit's fixed capacity in pump mode at the *t*-th hour, MW; η_{pump} — efficiency coefficient in pump mode; P_{tran} — electricity transmission tariff [28], €/MWh; $P^{t}_{r\ mark}$ — the electricity market price at hour *t*, €/MWh; β^{t}_{pump} — Boolean (decision) variable (1 — in pump mode); $\beta^{t}_{FPV,p}$ — Boolean (decision) variable (1 — in pump mode).

The first addend of the summation in the objective function denotes the income from the PSHP produced energy sold in the market. The second addend is the income gained from selling the FPV production; the third – the value of the energy consumed by the PSHP in pumping mode (hence the negative sign), and, finally, the fourth addend is the value of the FPV produced energy used for powering the pumps (i.e., it is the avoided cost incurred by producing energy for powering the pumps locally, instead of purchasing it from the market).

The solution of the problem (3) should be carried out taking into account the constraints as follows:

$$\begin{cases} H_{min} \le \sum_{t=1}^{T_{pl}} \left(H_{init} + \sum_{n=1}^{M} H_{dis} \cdot (-\beta^{n,t}_{gen} + \beta^{n,t}_{pump}) \right) \le H_{max}, \\ \sum_{t=1}^{T_{pl}} \sum_{n=1}^{M} H_{\Delta} \cdot (-\beta^{n,t}_{gen} + \beta^{n,t}_{pump}) = H_{init} - H_{final} \\ \beta^{t}_{FPV,g} + \beta^{t}_{FPV,p} \le 1, \forall t \in T \\ \beta^{t}_{FPV,p} = \beta^{n,t}_{pump}, \forall t \in T, \forall n \in M \\ \beta^{n,t}_{gen} + \beta^{n,t}_{pump} \le 1, \forall t \in T, \forall n \in M \end{cases} \qquad (4)$$

where H_{Δ} — water discharge/charge during operation of one unit for one hour in order to generate rated power or pump with maximal capacity respectively, m; H_{min} — minimal water level of PSHP reservoir, m; H_{max} — maximal water level of PSHP reservoir, m; H_{init} — initial water level of PSHP reservoir, m; H_{final} — final water level of reservoir, m; *N* — total number of generation units; *n* — index of generation unit.

The problem represented by expressions (3) and (4) contains Boolean variables and could be solved using mixed integer linear programming, but in the formulation under consideration, the length of the planning period in (3) and initial and final water level of PSHP reservoir are additional unknowns, which prevents the direct use of linear programming. Fortunately, this problem can be overcome by treating named parameters as hidden variables [29] and looking for its value based on a simple enumeration method [25].

C. *Forecasting of state variables*

To predict electricity prices, we use the time series of Nord Pool 2018 historical data [30] (see Fig. 1) and a naive approach, that is, we assume that the prices of the previous year (records of 2018 were used) will be repeated in the future.

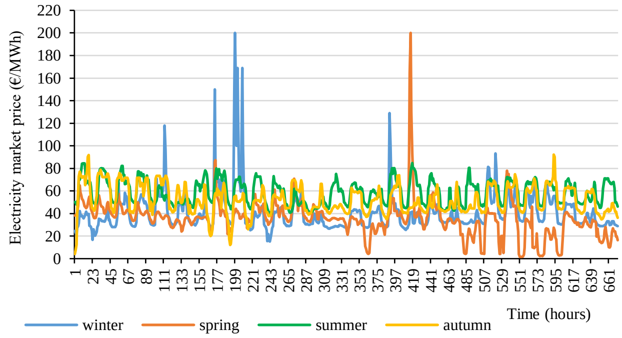

Fig. 1. Historical hourly electricity market price for LV bidding area

To predict the production of solar energy, we utilize the well-known approach [31] based on the lagging time series of production records of neighbouring photovoltaic plants. For this, during 2018, records of the generation of 20 distributed PV plants with a total capacity of 60 kW were collected [32, 33]. The generation volume of an FPV plant is estimated (example see Fig. 2) by introduction of a scaling factor. Forecasts are based on a naïve approach, i.e. we assume that annual generation will be repeated each year of the planning period.

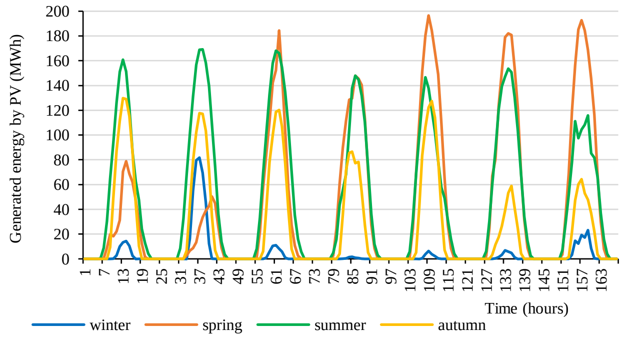

Fig. 2. Prediction of PV plant power generation

D. *Results*

The following assumptions and conditions are taken into account:

- The final water level is constrained to equal the initial level in all the simulations performed, i.e., the second constraint in (4) additionally has an 'equal to zero' condition.

- The profit dependence on the initial water level is tested for different planning periods (168, 336 and 672 hours).
- The beginning of the planning period in all cases coincides with the commencement of the work week.
- Optimisation problem (3)–(4) is solved using the computing environment for engineers and scientists, namely, MATLAB 2018b, with the optimisation toolbox and respective mixed-integer linear programming (MILP) optimisation solver – “intlinprog” [34]. Duration of 168 hours planning period optimisation is approximately 10 seconds.

Fig. 3-6 outline (FPV-PSHP + TSO) profit dependence on the initial reservoir water level. Informative text boxes show water level in PSHP reservoir and the respective profit in the cases of the highest (circle markers) and lowest (diamond markers) profitability for the considered planning periods.

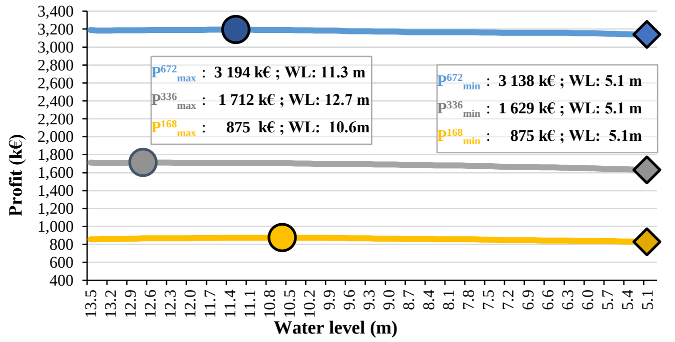

Fig. 3. FPV-PSHP + TSO profit dependence on the initial water level for planning periods 31/07/2018 - 06/08/2018 (yellow), 31/07/2018 - 13/08/2018 (grey), 31/07/2018 - 27/08/2018 (blue)

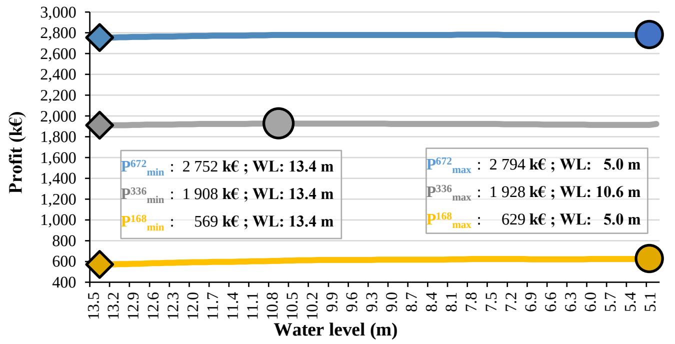

Fig. 4. FPV-PSHP + TSO profit dependence on the initial water level for planning periods: 15/01/2018 - 21/01/2018 (yellow), 15/01/2018 - 28/01/2018 (grey), 15/01/2018 - 11/02/2018 (blue)

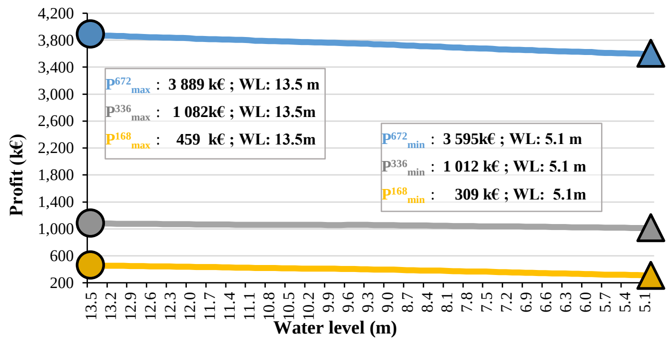

Fig. 5. FPV-PSHP + TSO profit dependence on the initial water level for planning periods: 16/04/2018 - 22/04/2018 (yellow), 16/04/2018 - 06/05/2018 (grey), 16/04/2018 - 13/05/2018 (blue)

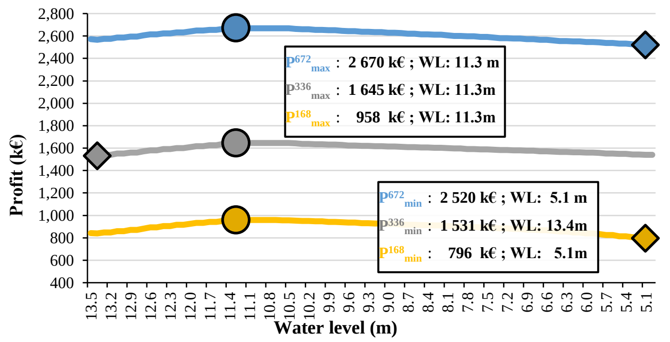

Fig. 6. FPV-PSHP + TSO profit dependence on the initial water level for planning periods: 15/10/2018 - 21/10/2018 (yellow), 15/10/2018 - 28/10/2018 (grey), 15/10/2018 - 11/11/2018 (blue),

Fig. 3–6 correspond to the different seasons of the year, and the blue, gray and yellow curves relate to differing lengths of the planning period (672 hours, 336 hours and 168 hours respectively). The presented curves allow us to conclude that there is a weak dependence of profit on the initial level of the reservoir. The exception is the winter season and the weekly planning period.

Once an optimal initial water levels are detected (Fig. 3-6) the FPV-PSHP profit can be calculated. Table II shows the dependence of FPV-PSHP profitability in different seasons of the year depending on the length of the planning period. For each of the subcases, the optimum initial/final water level is selected and presented, i.e., the one providing the largest profit for the particular time horizon. Furthermore, unlike in the calculations for the cases in Fig. 3–6, for the results in Table II, the transmission tariff for consumed energy is disregarded.

TABLE II. WATER LEVEL VARIATION AND FINAL PROFIT AFTER OPTIMISATION OF FPV-PSHP WITH DIFFERENT PLANNING PERIODS

Planning period (h)	Water level (m)	Week 1	Week 2	Week 3	Week 4	Profit (k€)
SUMMER						
672	$H_{initial}$	11.30	10.59	11.30	11.30	2 756
	H_{final}	10.59	11.30	11.30	11.30	
336	$H_{initial}$	12.70	10.57	12.70	11.28	2 758
	H_{final}	10.57	12.70	11.28	12.70	
168	$H_{initial}$	10.60	10.60	10.60	10.60	2 749
	H_{final}	10.60	10.60	10.60	10.60	
AUTUMN						

672	$H_{initial}$	11.30	7.94	5.11	12.00	2 135
	H_{final}	7.94	5.11	12.00	11.30	
336	$H_{initial}$	11.30	7.94	11.30	12.00	2 128
	H_{final}	7.94	11.30	12.00	11.30	
168	$H_{initial}$	11.30	11.30	11.30	11.30	2 115
	H_{final}	11.30	11.30	11.30	11.30	
WINTER						
672	$H_{initial}$	5.00	10.66	11.37	13.49	2 228
	H_{final}	10.66	11.37	13.49	5.00	
336	$H_{initial}$	10.60	10.60	10.60	13.43	2 193
	H_{final}	10.60	10.60	13.43	10.60	
168	$H_{initial}$	5.00	5.00	5.00	5.00	1 972
	H_{final}	5.00	5.00	5.00	5.00	
SPRING						
672	$H_{initial}$	13.50	11.38	5.00	11.38	3 432
	H_{final}	11.38	5.00	11.38	13.50	
336	$H_{initial}$	13.50	11.38	13.50	11.38	3 291
	H_{final}	11.38	13.50	11.38	13.50	
168	$H_{initial}$	13.50	13.50	13.50	13.50	3 224
	H_{final}	13.50	13.50	13.50	13.50	

The results presented in Table II reflect the dependence of the four-week profit on the duration of the planning period. In cases where the planning period was chosen equal to one or two weeks, the calculation of monthly profit was carried out by repeating the weekly (or biweekly) planning for a period of a whole month. As one would expect, the greatest profit can be obtained with the longest planning period. However, its growth compared to the two-week period is insignificant (4% in spring). At the same time, a short planning period (one-week) leads to a loss of profit of 10% (in winter) compared to the two-week case. The obtained estimates of profit allow us to conclude that it is most constructive to select the duration of the planning period equal to two or more weeks.

III. Conclusions

- The choice of the operating mode of storage power plants can be made on the basis of the formulation and solution of a complex optimisation problem that requires prediction of the processes of price changes and power generation for a long period and with high resolution.
- In the tasks of optimizing the management of the operating modes of energy storage power plants, it becomes necessary to decompose them in time, to choose the duration of the planning period and the initial and final state of energy storage systems.
- An increase in the duration of the planning period leads to an increase in profit and a decrease in dependence on the initial and final state of storage systems. However, this effect weakens when the duration of the planning period is equal to two weeks or more.
- The use of integer linear programming provides an acceptable time to search for the optimal solution. Optimisation problem can be solved using the computing environment MATLAB 2018b` release with appropriate optimisation toolbox and respective mixed-integer linear programming (MILP) optimisation solver – "intlinprog".

IV. References

[1] A. G. Kagiannas, D. T. Askounis, and J. Psarras, "Power generation planning: a survey from monopoly to competition," Int. J. Electr. Power Energy Syst., vol. 26, no. 6, pp. 413–421, Jul. 2004.

[2] S. Spiecker and C. Weber, "The future of the European electricity system and the impact of fluctuating renewable energy – A scenario analysis," Energy Policy, vol. 65, pp. 185–197, Feb. 2014.

[3] T. Jónsson, P. Pinson, and H. Madsen, "On the market impact of wind energy forecasts," Energy Econ., vol. 32, no. 2, pp. 313–320, Mar. 2010.

[4] G. Papaefthymiou and K. Dragoon, "Towards 100% renewable energy systems: Uncapping power system flexibility," Energy Policy, vol. 92, pp. 69–82, May 2016.

[5] P. Nema, R. K. Nema, and S. Rangnekar, "A current and future state of art development of hybrid energy system using wind and PV-solar: A review," Renew. Sustain. Energy Rev., vol. 13, no. 8, pp. 2096–2103, Oct. 2009.

[6] B. V. Mathiesen et al., "Smart Energy Systems for coherent 100% renewable energy and transport solutions," Appl. Energy, vol. 145, pp. 139–154, May 2015.

[7] Broka, Z., Kozadajevs, J., Sauhats, A., Finn, D., Turner, W. Modelling Residential Heat Demand Supplied by a Local Smart Electric Thermal Storage System. In: 2016 57th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON 2016): Proceedings, Latvia, Riga, 13-14 October, 2016.

[8] X. Luo, J. Wang, M. Dooner, J. Clarke, and C. Krupke, "Overview of Current Development in Compressed Air Energy Storage Technology," Energy Procedia, vol. 62, pp. 603–611, 2014.

[9] H. Ibrahim, K. Belmokhtar, and M. Ghandour, "Investigation of Usage of Compressed Air Energy Storage for Power Generation System Improving - Application in a Microgrid Integrating Wind Energy," Energy Procedia, vol. 73, pp. 305–316, Jun. 2015.

[10] P. Kanakasabapathy and K. Shanti Swarup, "Optimal bidding strategy for multi-unit pumped storage plant in pool-based electricity market using evolutionary tristate PSO," in 2008 IEEE International Conference on Sustainable Energy Technologies, 2008, no. December, pp. 95–100.

[11] P. Kanakasabapathy and K. Shanti Swarup, "Pumped storage bidding and its impacts in combined pool-bilateral market," in 2009 International Conference on Power Systems, 2009, pp. 1–6.

[12] A. Spisto, "Market valuation of a hypothetical pump-hydro storage plant in the Italian power system," in 11th International Conference on the European Energy Market (EEM14), 2014, pp. 1–5.

[13] J. F. Bolado, H. L. Ferreira, and W. Kling, "Energy storage market value - A Netherlands case study," in 2014 49th International Universities Power Engineering Conference (UPEC), 2014, pp. 1–6.

[14] Kozadajevs, J., Broka, Z., Sauhats, A. Modelling Heat Demand in Buildings with an Experimental Approach. In: 2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Italy, Milan, 6-9 June, 2017.

[15] B. Zakeri and S. Syri, "Economy of electricity storage in the Nordic electricity market: The case for Finland," in 11th International Conference on the European Energy Market (EEM14), 2014, pp. 1–6.

[16] Liang Liang, Li Jianlin, and Hui dong, "An optimal energy storage capacity calculation method for 100MW wind farm," in 2010 International Conference on Power System Technology, 2010, pp. 1–4.

[17] Moitre, D., Alemany, J. M., Pinto H., Magnago F. Short-Term Scheduling of Combined Cycle Units Using Mixed Integer Linear Programming Solution. In: January 2013 Energy and Power Engineering Volume 5 (Issue 2): pp. 161-170.

[18] Shuang Yu, T. J. Mays, and R. W. Dunn, "A new methodology for designing hydrogen energy storage in wind power systems to balance generation and demand," in 2009 International Conference on Sustainable Power Generation and Supply, 2009, vol. 1–4, pp. 1–6.

[19] I. M. Viola, G. P. Harrison, A. Dunbar, and F. Tagliaferri, "The impact of electricity price forecast accuracy on the optimality of storage revenue," in 3rd Renewable Power Generation Conference (RPG 2014), 2014, pp. 8.17-8.17.

[20] A. Wilson, R. Webster, B. P. Hayes, and S. Z. Djokic, “Comparison of two energy storage options for optimum balancing of wind farm power outputs,” IET Gener. Transm. Distrib., vol. 10, no. 3, pp. 832–839, Feb. 2016.

[21] Sauhats, A., Petričenko, R., Baltputnis, K., Broka, Z., Varfolomejeva, R. A Multi-Objective Stochastic Approach to Hydroelectric Power Generation Scheduling. In: 2016 Power Systems Computation Conference (PSCC 2016), Italy, Genoa, 20-24 June, 2016.

[22] Sauhats, A., Coban, H., Baltputnis, K., Broka, Z., Petričenko, R., Varfolomejeva, R. Optimal Investment and Operational Planning of a Storage Power Plant. International Journal of Hydrogen Energy, 2016, Vol.41, Iss.29, pp.12443-12453.

[23] Powell W. B.; Meisel S. Tutorial on Stochastic Optimisation in Energy Part I: Models and Policies, IEEE Trans. on Power Systems, 2016, 31(2), 1459-1467.

[24] Nguyen T. A.; Byrne R. H. Maximizing the cost-savings for time-of-use and net-metering customers using behind-the-meter energy storage systems, 2017 North American Power Symposium (NAPS), Morgantown, WV, 2017, pp. 1-6. doi: 10.1109/NAPS.2017.8107380

[25] Petričenko, Ļ., Petričenko, R., Sauhats, A., Baltputnis, K. Avoided Costs-Based Comparison of Consumer-Scale Energy Storage Control Approaches. In: 2019 16th International Conference on the European Energy Market (EEM 2019), Slovenia, Ljubljana, 18-20 September, 2019.

[26] Kruonis Pumped Storage Hydroelectric Plant (the KPSHP): brief overview. Available online: https://ignitisgamyba.lt/en/our-activities/electricity-generation/kruonis-pumped-storage-hydroelectric-plant-the-kpshp/4188 (accessed on 29 March 2020).

[27] Hydro review newsletter online source: https://www.hydroreview.com/2019/02/27/floating-solar-photovoltaic-plant-to-be-installed-at-kruonis-pumped-storage-plant-in-lithuania/#gref

[28] Agency for the Cooperation of Energy Regulators (ACER) Practice report on transmission tariff methodologies in Europe. Avaliable online: https://www.acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/ACER%20Practice%20report%20on%20transmission%20tariff%20methodologies%20in%20Europe.pdf

[29] Baltputnis, K., Broka, Z., Sauhats, A., Petričenko, R. Short-Term Optimization of Storage Power Plant Operation under Market Conditions. In: 2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC 2016), Italy, Florence, 7-10 June, 2016. Piscataway, NJ: IEEE, 2016, pp.250-255. ISBN 978-1-5090-2321-9. e-ISBN 978-1-5090-2320-2. (Scopus, WoS) doi: 10.1109/EEEIC.2016.7555466

[30] Nord Pool electrical energy price statistics. Available online: http://www.nordpoolspot.com/Market-data1/Elspot/Area-Prices/

[31] J. Antonanzas; N. Osorio ; R. Escobar ; R. Urraca ; F. Martinez-de-Pison ; F. Antonanzas-Torres. Review of photovoltaic power forecasting. Sol Energy, 2016, 136, 78-111.

[32] SolarEdge database. Available online: https://monitoringpublic.solaredge.com/solaredge-web/p/home/public?locale=en_US (accessed on 6 April 2020.).

[33] Official Statistics Solar photovoltaic (PV) cost data, 2014. Available online: https://www.gov.uk/government/statistics/solar-pv-cost-data (accessed on 23 April 2020).

[34] Mixed-integer linear programming (MILP). Available online: https://se.mathworks.com/help/optim/ug/intlinprog.html (accessed on 21 March 2020).

This is a post-print of a paper published in Proceedings of the 2020 IEEE 61st International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON 2020) and is subject to IEEE copyright.
https://doi.org/10.1109/RTUCON51174.2020.9316613
Electronic ISBN: 978-1-7281-9510-0.
USB ISBN: 978-1-7281-9509-4.
Print on Demand (PoD) ISBN: 978-1-7281-9511-7.