Renewable Energy 195 (2022) 780–794

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Utilization of excess water accumulation for green hydrogen production in a run-of-river hydropower plant

David Jure Jovan *, Gregor Dolanc , Boštjan Pregelj

Department of Systems and Control, Jožef Stefan Institute, Jamova cesta 39, 1000, Ljubljana, Slovenia

A R T I C L E I N F O

Article history:
Received 2 February 2022
Received in revised form
2 June 2022
Accepted 15 June 2022
Available online 20 June 2022

Keywords:
Green hydrogen
Hydropower plant
Power-to-gas
Hydrogen production cost

A B S T R A C T

This paper discusses the potential for green-hydrogen production in a run-of-river hydropower plant. This particular hydropower plant has no significant water accumulation, but there is the potential for limited hydrogen production due to a mismatch between the daily predefined electricity production (known as the timetable) and the actual water inflows. The timetable for the hydropower plant is prepared by the operator of the electro-energetic system based on a model of the available production capacities, forecasted consumption, water accumulation, state of the river flows, weather forecasts and the system operator's strategy. The uncertainty in the model's input parameters is reflected in the output timetable for the hydropower plant and, for this reason, a small reserve of water for potential exploitation is envisaged. By using real data for the timetable and the water inflow, we estimate the excess hydropower that can be used for hydrogen cogeneration. Since the primary task of the hydropower plant is to produce electricity according to the timetable, the production of hydrogen is only possible to a limited extent. Therefore, we present a control algorithm that regulates the amount of hydrogen production, while considering the predefined timetable and the real water accumulation. The second part of the paper deals with the economic viability of hydrogen cogeneration in the case-study run-of-river hydropower plant and discusses the possibility of using it for local public transport.

1. Introduction

The integration of renewable energy sources (RESs), e.g., wind, photovoltaic, hydropower, is an effective way to meet the demands of increasing energy consumption, air pollution and climate change. In 2020, hydropower generated one-sixth of global electricity, making it the third-largest energy source after coal and natural gas. Hydropower's contribution is more than half that of nuclear power and greater than that of all the other RESs combined. Compared to wind turbines and photovoltaic fields, hydropower plants (HPPs) are the least weather dependent. As a result, hydropower remains the backbone of low-carbon electricity generation, providing almost half of it today [1]. However, the high share of RESs in the electricity network leads to challenges in managing the network and volatility in electricity prices due to the intermittent nature of RESs.

Power-to-gas (P2G) [2–4] is one of the new technologies that can provide solutions to the above-mentioned problems: the conversion of excess, renewable electrical energy into hydrogen makes it possible to store this energy; alternatively, the hydrogen can be used as a fuel for carbon-free transport, as a feedstock for the chemical industry, or as a component for renewable chemicals like methanol, ammonia, and synthetic natural gas. In this way, hydrogen can help stabilize electro-energetic systems that have a large share of RESs as well as contributing to the decarbonisation of society [5,6]. Furthermore, the hydrogen produced with electricity from RESs has an added value, because its production is CO_2-emission free, and, consequently, it can be referred to as “green hydrogen” [7].

Today's green-hydrogen technologies are rarely economically viable due to the price of the equipment needed for its production, which is not yet on the scale of mass production. This prevents green-hydrogen technologies from being more widely adopted. Many studies have addressed this issue and claim that the transition to RESs will inevitably need subsidies in the short-to-medium term [8–13]. These supporting policies must be accompanied by reduced costs to make the technologies a realistic alternative for

* Corresponding author.
E-mail address: david.jovan@ijs.si (D.J. Jovan).

https://doi.org/10.1016/j.renene.2022.06.079

Nomenclature acronyms

RES	Renewable energy sources
P2G	Power-to-gas system
CO_2	Carbon dioxide
HPP	Hydropower plant
NPP	Nuclear power plant
TPP	Thermal power plant
PV	Photovoltaics

Parameters and variables

Accum_inflow	Hydropower plant water inflow [m^3/s]
P_PV	Electric power obtained from photovoltaic system [MW]
P_TT	Electric power production according to the hydropower plant's timetable [MW]
P_{H2_demand}	Simulated hydrogen consumption [kg/d]
h_fall	Accumulation basin water level [m]
P_P2G_req	Required energy consumption for P2G system's operation [MW]
V_accum	Accumulation basin volume [m^3]
P_P2G	Actual energy consumption for P2G system's operation [MW]
ṁ_H2	Hydrogen production flow [kg/h]
ṁ_H2_demand	Simulated hydrogen demand [kg/h]
p_H2_storage	Current hydrogen pressure in storage tank [bar]
ṁ_H2_cons_allowed	Allowed hydrogen consumption [kg/h]
ELEC_prod	Amount of electricity produced [MW]
H2_prod	Amount of hydrogen produced [kg/h]
Profit_ELEC	Profit from electricity production [€]
Profit_H2	Profit from hydrogen production [€]
H2_PC_avg	Average price for hydrogen production [€/kg]
ṁ_H2_in	Amount of hydrogen produced [kg/h]
ṁ_H2_out	Amount of hydrogen consumed [kg/h]

the future. A similar opinion is expressed in Ref. [14], where the authors report that green hydrogen for road transport (in China) could be competitive against grey hydrogen in terms of cost, but new market mechanisms and appropriate policies would be necessary. The authors of [15] note that in a hybrid system where P2G provides a real option between the electricity and hydrogen markets, hydrogen values greater than €4/kg are required to provide an equal or greater net present value than an offshore wind farm producing only electricity. An engineering economic analysis [16] suggests that the green-hydrogen economy will be a profitable option for industrial decarbonisation, and it will be more viable in cases that include carbon taxes, and will become more profitable as hydrogen production costs begin to decrease from €9/kg. In Ref. [17] the author concludes that green hydrogen is seen by investors, developers, and politicians as a strong enabler to meet net-zero targets and that a market for green hydrogen is opening up, but cost competitiveness remains a barrier to scaling up.

Although Slovenia has not yet prepared and adopted its hydrogen strategy, it is already running some initiatives for the production and use of green hydrogen among stakeholders in the national electricity system. One of the results was a feasibility study [18] of a case-study Slovenian HPP, where the aim was to estimate the economic viability of green-hydrogen production from the HPP's hydropower reserves. One of the conclusions of the study was that the HPP has some water reserves resulting from a mismatch between the daily required electricity production and the actual water inflow. This excess water power can be used to produce a limited amount of hydrogen [19].

To verify the hypothesis, this paper has three objectives. First, to describe the case-study HPP and its detailed model, augmented with a P2G system model. The complete model contains both a physical model and an economic model of its operation and serves as a basis for a series of simulation runs in which we realistically assess the idea of concurrent hydrogen production using real data for the case-study HPP's operating conditions (i.e., the demanded electricity production) and the current market prices for electricity and hydrogen.

The next objective was to design a control algorithm for the P2G system that would enable the cogeneration of smaller amounts of green hydrogen during periods of excess water accumulation in the HPP case study, while meeting the prescribed timetable for electricity production. The final objective was to evaluate the economic viability of electricity and hydrogen cogeneration in the case-study HPP and in an extended PV scenario, which might suffer from some inaccuracies due to the uncertain price situation in the global energy market in recent months.

The results of the article could have a positive impact on current societal challenges in terms of decarbonisation, environmental protection and hydropower efficiency. The dynamic operation of the P2G system during periods of excess hydropower can ensure the production of green hydrogen for local needs and contribute to a more efficient HPP. Depending on the installed capacity of the P2G system, its dynamic operation could also have a positive impact on the riverine ecosystem [20] as the extent of water accumulation denivelation would be reduced.

The novelty lies in the design of the appropriate configuration of the P2G system for the cogeneration of electricity and green hydrogen, based on an assessment of the excess water energy in the case-study run-of-river HPP. The design of the P2G system considers the requirement for predefined regular electricity production (known as the timetable), the cost of installing the P2G system and the assessment of the resulting financial effects.

The article is structured as follows. After the introduction, a brief description of the electro-energetic system's management in Slovenia and the case-study HPP is presented together with real data from the daily timetable for electricity production and actual water inflows for one month. The next section describes a MATLAB/Simulink model of the case-study HPP, developed to perform simulations based on real data to determine the most appropriate configuration of the P2G system, the parameters of the P2G system's control algorithm, the amount of hydrogen produced, and the profit from hydrogen production. This section also analyses the cost structure of hydrogen production, evaluates the economic viability of the hydrogen production in the case-study HPP, and the possibility of using the produced green hydrogen for a bus in a local community. The concluding part includes a discussion of the advantages of including a photovoltaic field in the operation of the HPP and gives some guidelines for future work.

2. Management of the electro-energetic system in Slovenia

Management of an electro-energetic system is focused on maintaining the balance between consumption and production. In general, an electricity grid is balanced with the following mechanisms: (i) long-term contracts among electricity producers and consumers, (ii) daily trading between producers and consumers on the electric-energy stock exchange using different instruments and products, and (iii) activation of ancillary services composed of primary, secondary and tertiary control [21]. Under normal conditions, an electro-energetic system's operator responds to the difference between current production and consumption by increasing/decreasing the current production in particular power plants to return the system to equilibrium.

The Slovenian system's operator maintains the balance between electricity production and consumption with a daily hour-based schedule for the next day that includes every production facility in the electro-energetic system. The system operator has three types of facilities available to produce electricity in Slovenia: (i) the nuclear power plant, (ii) thermal power plants, and (iii) RES, where the vast majority of the electric energy comes from HPPs (because the share of photovoltaic and wind electricity in Slovenia is negligible). Most Slovenian HPPs are of the “run-of-river” type [22]. Consequently, they have limited storage capacity behind the dam and electricity generation is dependent on timing and the size of the river flow. An additional feature is that they mostly occur in a cascade, where the highest power plant usually has a larger water accumulation, which is then used by the hydropower plants downstream. Consequently, each HPP in the cascade has restrictions on the use of its accumulated water, which are defined by the allowed denivelation of its accumulated water and the discharge rate.

As an example, Fig. 1 shows the actual and planned electricity consumption in Slovenia. Deviations between the actual production and consumption of electricity are solved by the system operator correcting the planned daily schedules for production facilities and using specific additional measures (purchase/sale of energy on the electricity market, ancillary services [21]).

From Fig. 2 we can see that the tracking of dynamic electricity consumption is ensured mainly by the production of electricity from hydropower sources. The Slovenian system operator makes every effort to obtain electricity from renewable sources. For this reason, the daily load schedule is made in such a way as to make the most of the potential of the HPPs.

However, the schedule for the HPPs is prepared on the basis of different models for the available production capacities, forecasted consumption, current water accumulation, the state of the river flows, weather forecasts, and the system operator's strategy. The uncertainty in the model's input parameters is also reflected in the output timetable for the individual HPP and, for this reason, a small water reserve is envisaged for potential exploitation. In practice, a certain part of the hydropower remains unused; this is reflected in more water being accumulated and, in some cases, of water spilling over the dam. Thus, a hydropower plant can, from time to time, exploit unused surplus hydropower to produce electricity for hydrogen production using the P2G system. Here, it should be noted that among RESs, HPPs are the least sensitive to weather conditions and, therefore, the most suitable for the regular production of electricity and green hydrogen.

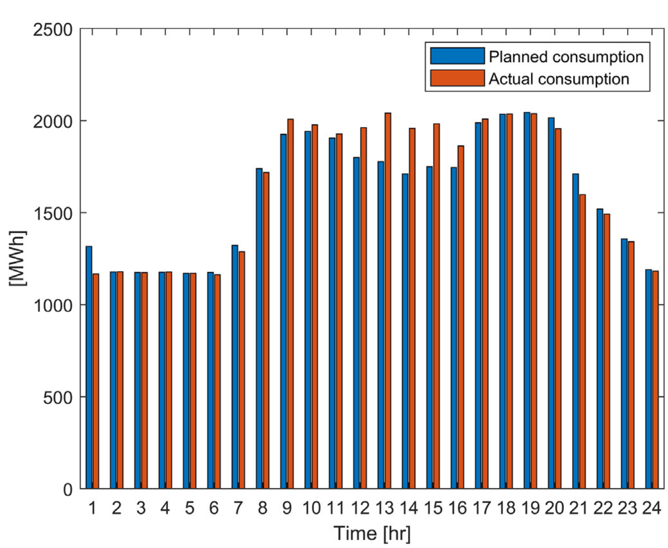

Fig. 1. Planned and actual daily electric energy consumption, Sep. 15, 2021.

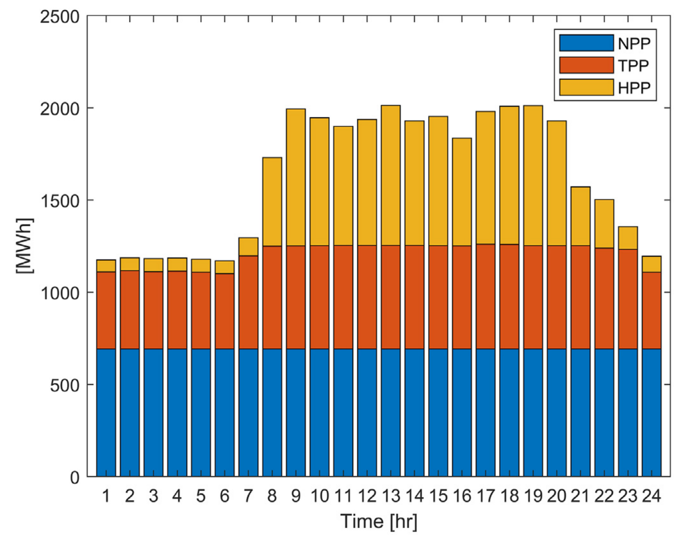

Fig. 2. Structure of electric energy production, Sep. 15, 2021 (blue: nuclear power plant, red: coal-fired power plants, orange: hydroelectric power).

3. The case-study hydropower plant

The case-study HPP is of the run-of-river and reservoir type. It is the last HPP in a cascade of five HPPs with an actual average power of around 18.4 MW due to the limitations of the seasonal water flow and its location in the cascade. Its total water accumulation is 19,300,000 m^3, but its useable water accumulation is only 3,400,000 m^3, due to a maximum operating denivelation level of 1.1 m. To increase its operating power, the case-study HPP will begin installing a new photovoltaic array of up to 10 MW of nominal power in the near future. The case-study HPP is located near two towns with a total population of 15,000 and is near a highway. So, the produced hydrogen could be delivered to both cities for local transport and heating, or to hydrogen filling stations along the highway.

Due to its flat location and inclusion in the chain with other hydropower plants, the case-study HPP has limited possibilities for water accumulation. The hourly defined timetable for the case-study HPP usually reflects the current water inflow, but in practice some minor water reserves are available. This situation is presented in Fig. 3 and Fig. 4, where Fig. 3 shows the hourly predefined timetable for the case-study HPP for one month and Fig. 4 shows the actual water inflow into the case-study accumulation basin. The one-month observation period was selected so that the initial accumulation of water was about half of the nominal.

The prescribed schedule generally corresponds to the actual inflow of water; however, all the accumulated water is not exploited. The difference between the actual water inflow and the required water inflow to meet the prescribed timetable is shown in Fig. 5. The cumulative excess water inflow for the observed month-long period is estimated to be around 5,000,000 m^3. This results in a high level of water accumulation and in occasional water spills over the case-study HPP's dam during some time periods (Fig. 6).

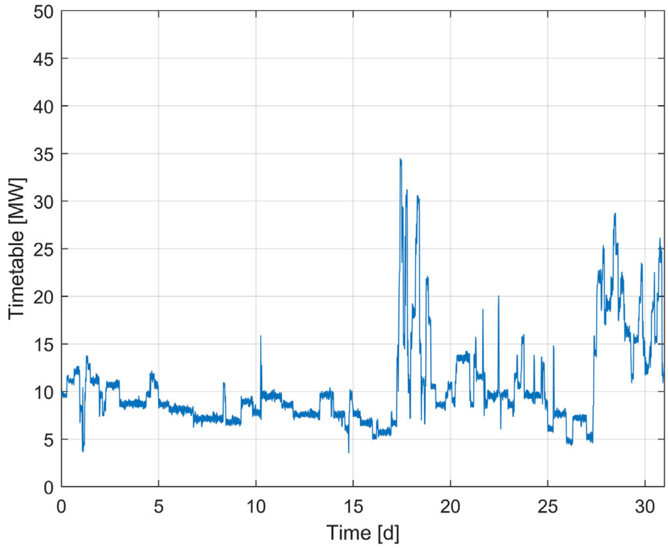

Fig. 3. Timetable for one month. The prescribed timetable results in a monthly electricity production of 7791 MWh.

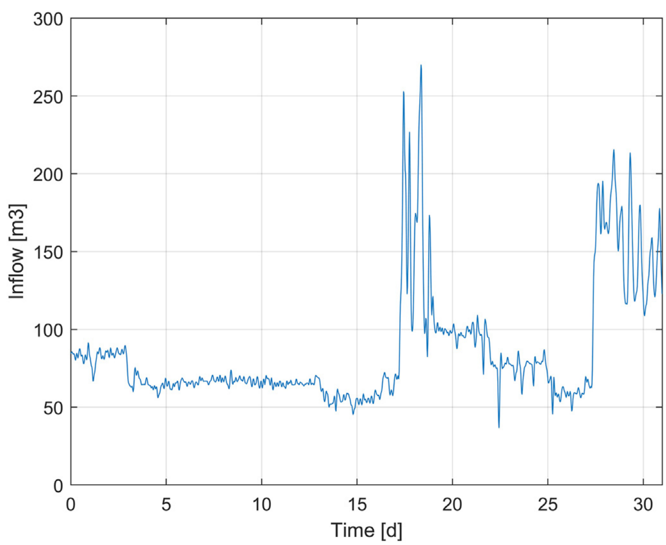

Fig. 4. Actual water inflows during one month.

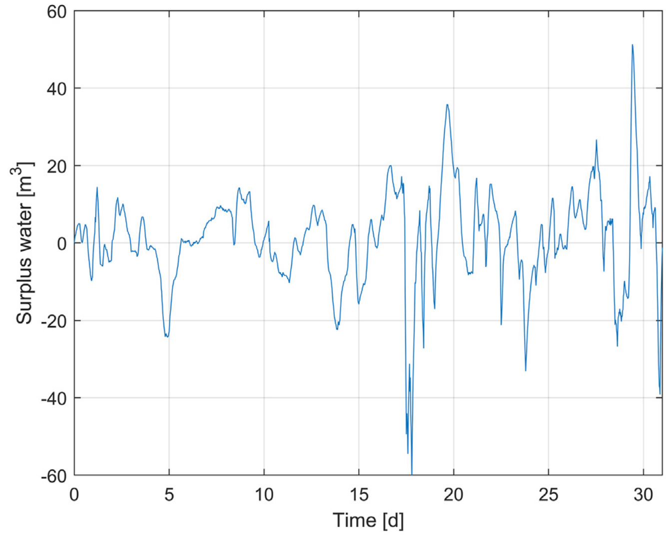

Fig. 5. Surplus of water inflow with respect to the timetable requirements.

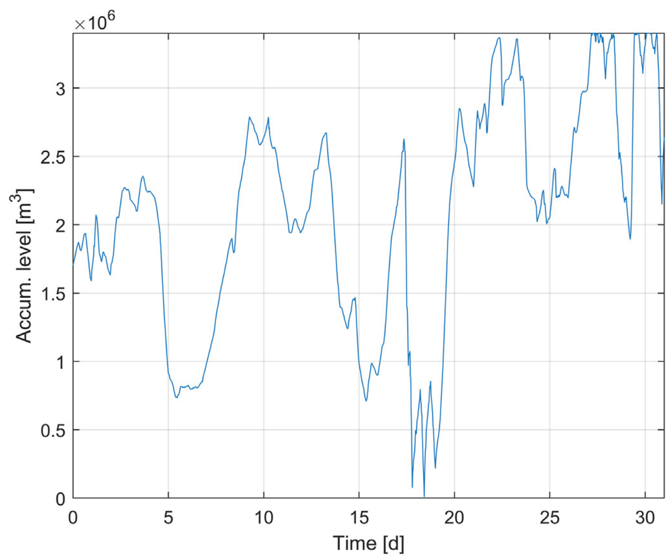

Fig. 6. Monthly water accumulation for the case-study HPP.

Therefore, the reserves in accumulated water enable the regular production of a limited amount of green hydrogen in the case-study HPP, which can be understood as a cogeneration of electricity and hydrogen. Cogeneration is defined as “the generation of two different forms of useful energy from a single primary energy source” [23].

The cogeneration of hydrogen along with the regular production of electricity in a HPP according to the prescribed timetable requires a suitable system for hydrogen production (P2G system), free capacities to produce the additional electricity for the P2G system, and sufficient water reserves.

In the following we will assess the possible volume of green-hydrogen production in the case-study HPP in Slovenia and give an assessment of the economic justification for its production.

4. Model of the case-study HPP

To estimate the amount of hydrogen that can be obtained during regular operation of the power plant we designed a model of the HPP resembling a conceptual scheme, given in Fig. 7, realized in the MATLAB/Simulink environment (Fig. 8).

The main inputs to the model are:

- Demanded electrical power (according to the timetable),
- Demanded hydrogen production,
- Current state of the HPP (water accumulation, actual water inflow, solar power),
- Current prices of electricity and hydrogen.

The developed Simulink model enables:

- Simulation of the case-study HPP's operation with the installed P2G system and hydrogen storage in various set-ups,
- Simulation of hydrogen consumption,
- The collection of operational parameters (electricity and hydrogen production, water accumulation level, pressure in hydrogen storage, P2G system efficiency, etc.),

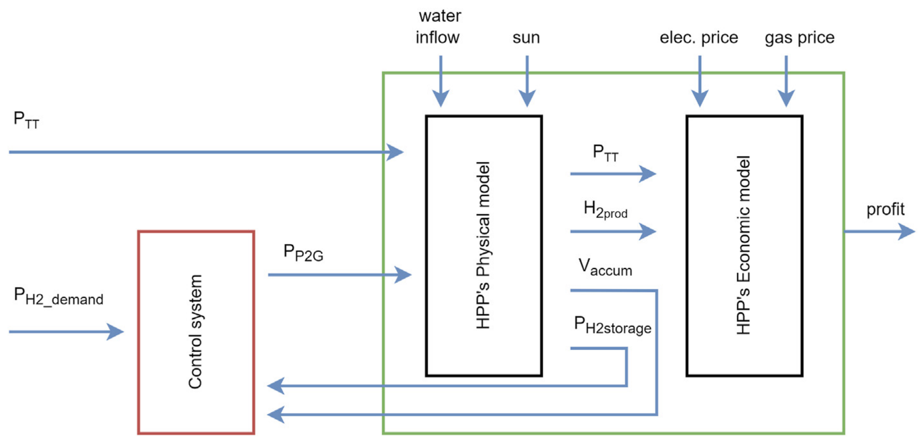

Fig. 7. Conceptual scheme of the developed case-study HPP model.

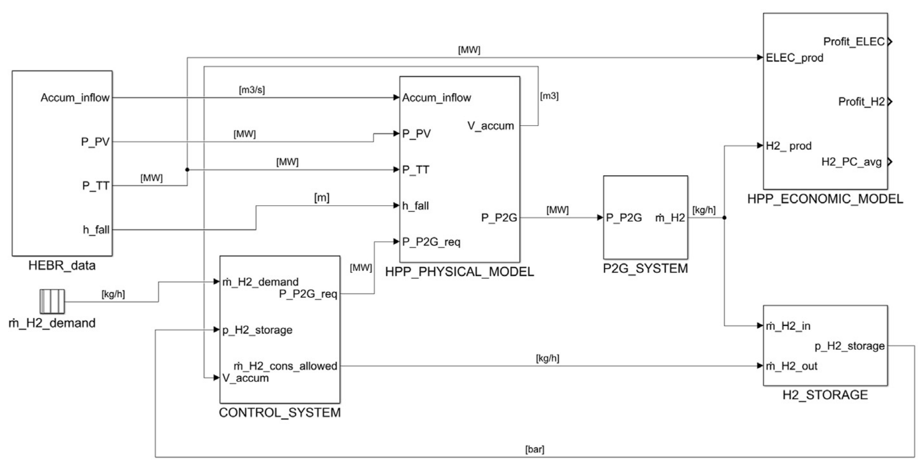

Fig. 8. Snapshot of MATLAB/Simulink scheme of the case-study HPP.

- An economic evaluation of electricity and hydrogen production, while considering installation and operating costs for the necessary equipment.

One of the main aims was to design an appropriate control system that enables the cogeneration of electricity and hydrogen with respect to the predefined timetable.

HPP_data module: prepares the real data of the water inflow, the real timetable defined by the system operator, the actual water drop and the simulated results of electricity production from the PV field.

HPP_PHYSICAL_MODEL: the model of the case-study HPP calculates its operating power using the real data of water flows and the actual water drop. The electricity produced must be in accordance with the schedule/timetable predefined by the system operator. The module updates the overall water accumulation of the HPP and identifies the difference between the demanded electric power according to the timetable (based on the system operator's model) and the electricity production that is possible (based on actual water inflows).

HPP_ECONOMIC MODEL: calculates the current production price of green hydrogen and the profit with respect to electricity and hydrogen market prices and the production costs for both electricity and hydrogen.

P2G_SYSTEM module: the identified excess electric power that can be used for hydrogen generation is the input to this module, which calculates the corresponding hydrogen volume reduced by the amount of energy required to compress the hydrogen.

H2_STORAGE module: defines the actual pressure in the hydrogen-storage tank according to hydrogen generation and consumption.

CONTROL_ SYSTEM module: calculates the actual electric power for the P2G system's operation. The P2G system's load depends on the actual water accumulation and the pressure in the hydrogen-storage tank. The calculated, assigned electrical power for the P2G system allows the electrolyser to operate most of the time at 20–80% of its nominal power (as the electrolyser operates most efficiently in this range). The P2G only shuts down in cases of a very low level of water accumulation or a full hydrogen-storage tank. The algorithm for determining the current load factor P of the electrolyser (current power load of electrolyser = P × nominal power of electrolyser) is shown in Fig. 9.

4.1. Configuration of the P2G system

From Section 3 we can conclude that the case-study HPP has a surplus of accumulated water and production reserves for the additional electric energy needed for hydrogen production. The first step is to determine the configuration of the P2G system (Fig. 10) that will be able to efficiently use the excess hydropower to produce the hydrogen.

The P2G system has four main building blocks: a power supply, an electrolyser, a hydrogen buffer-tank system together with water-fraction separation components, and final hydrogen storage before its distribution to consumers or other processes.

4.2. Simulations

The developed Simulink model was used to perform a number of simulations to determine the parameters for the P2G system. Some basic assumptions for the P2G system's parameters and its configuration were defined in advance:

- The P2G system should operate only when there is surplus water energy.

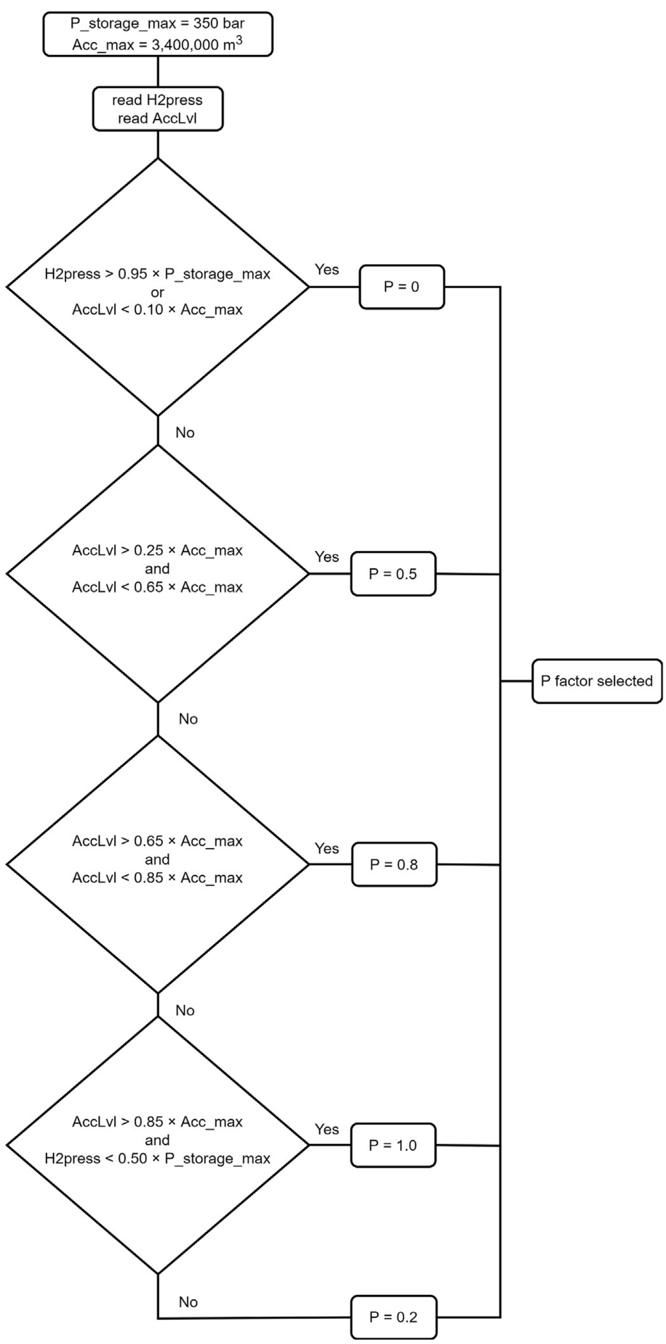

Fig. 9. Flowchart to determine the current electrolyser's operating power.

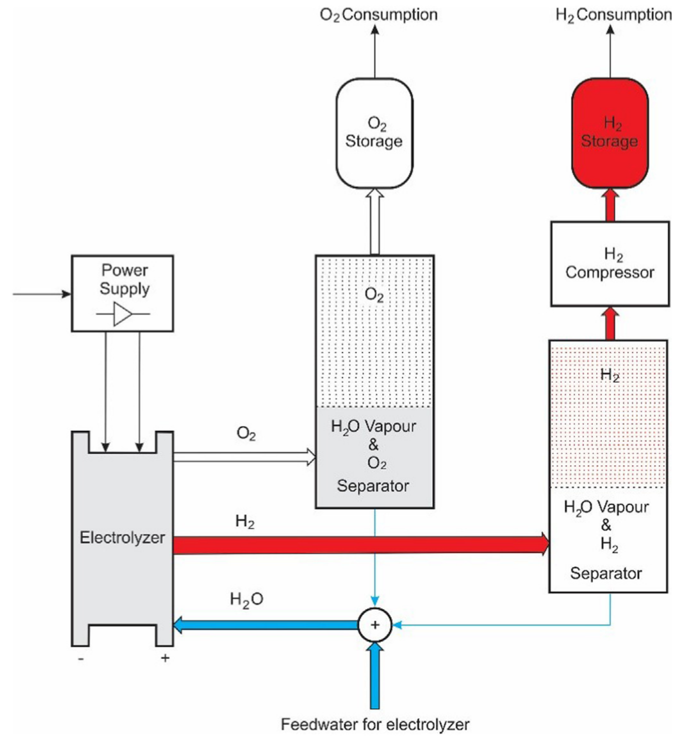

Fig. 10. Basic components of the P2G system.

- The P2G system's operating mode should be more-or-less continuous and preferably 20–80% of its nominal power (for optimum efficiency) and with the minimum number of starts and shutdowns.
- The P2G system's hydrogen storage should have a maximum pressure of 350 bars and sufficient reserves for 2–3 days.
- The P2G system should have a capacity of around 5000 kg of hydrogen per month.

The most important task is to choose the right capacity for the installed electrolyser. To determine its optimum nominal power, we used the developed HPP model, where real data of the water inflow, the defined timetable, and all the above assumptions and limitations were considered. We assumed that the hydrogen store is about half full at the beginning and that some of the electricity is also needed for compression of the produced hydrogen [24].

In a series of simulations (Figs. 11–17) we changed the nominal power of the electrolyser from 0.5 to 2 MW, with a step of 0.25 MW. The results of the simulations are shown in Figs. 11–17, where for each power chosen for the electrolyser, the time diagrams of the water accumulation and the electrolyser's load are shown.

The results of the simulation are summarized in Table 1.

As the efficiency of the P2G system drops with an increase in power (Fig. 18) and the amount of hydrogen produced is approaching saturation (Fig. 19), due to the limited amount of available electricity for the operation of the P2G system, the choice of a 1-MW P2G system is the best solution for the case-study HPP. The simulations also show that a volume of 15 m^3 for the hydrogen-storage reservoir is a sufficient reserve for 2–3 days.

4.3. Green-hydrogen production costs

In this section we will estimate the costs of purchasing and operating the necessary equipment for hydrogen production and the hydrogen production costs for the case-study HPP. For further

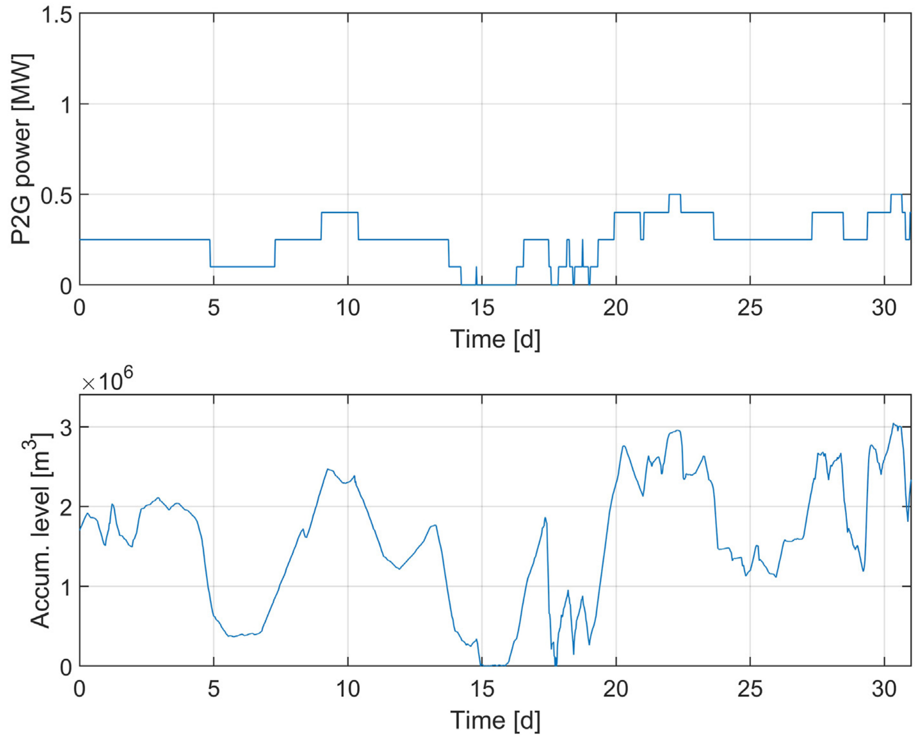

Fig. 11. Operation of a 0.5-MW electrolyser and water accumulation over a period of one month.

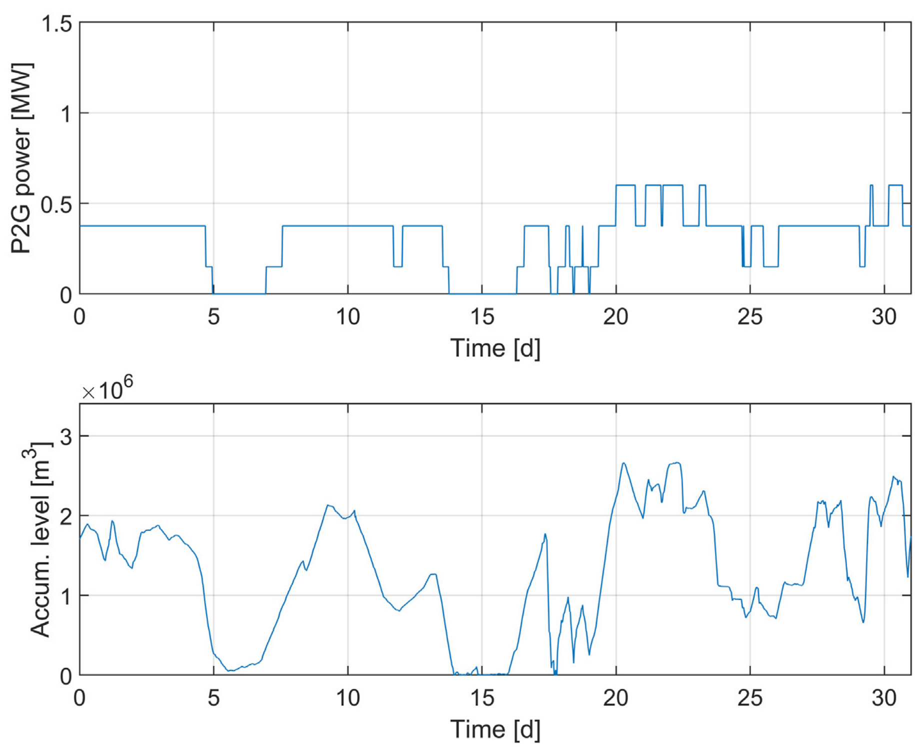

Fig. 12. Operation of a 0.75-MW electrolyser and water accumulation over a period of one month.

calculations, the technical specifications of one of the commercially available P2G systems [25] are used.

Considering the specific density of hydrogen (0.08988 kg/Nm^{3}) and its lower heating value (119.96 MJ/kg, i.e., 33.32 kWh/kg or 3.00 kWh/Nm^{3}) and the 1-MW P2G system's technical specifications [25], the maximum daily production of hydrogen is around 27 kg/h and the electric power consumption at the maximum production rate is 48.95 kWh/kg.

On the basis of the offers from some commercial providers of P2G systems and literature data [2,4,26–29] the main estimated

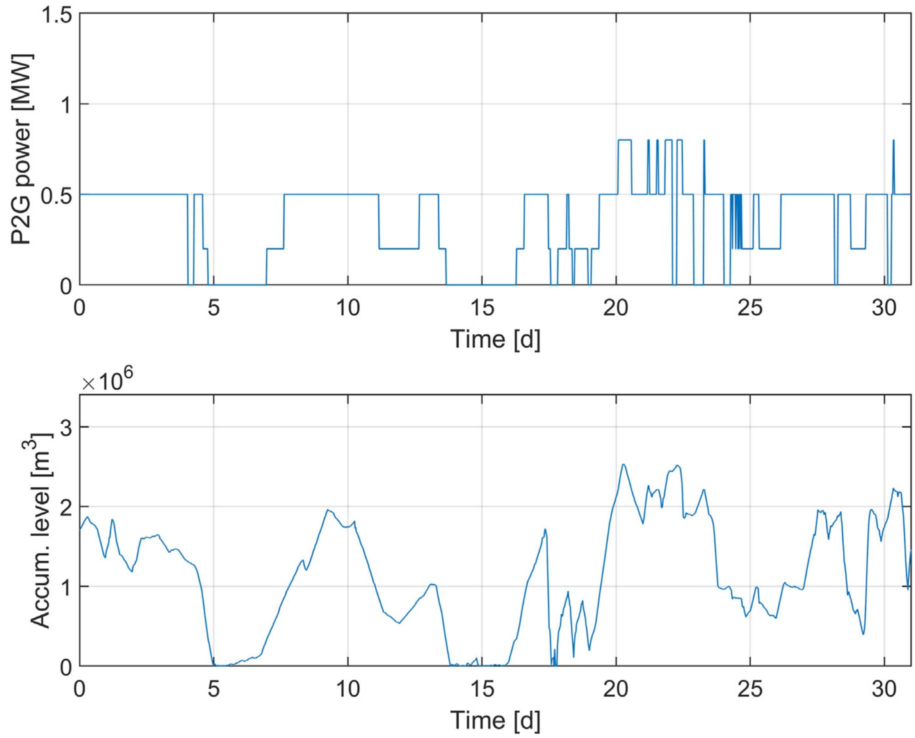

Fig. 13. Operation of a 1-MW electrolyser and water accumulation over a period of one month.

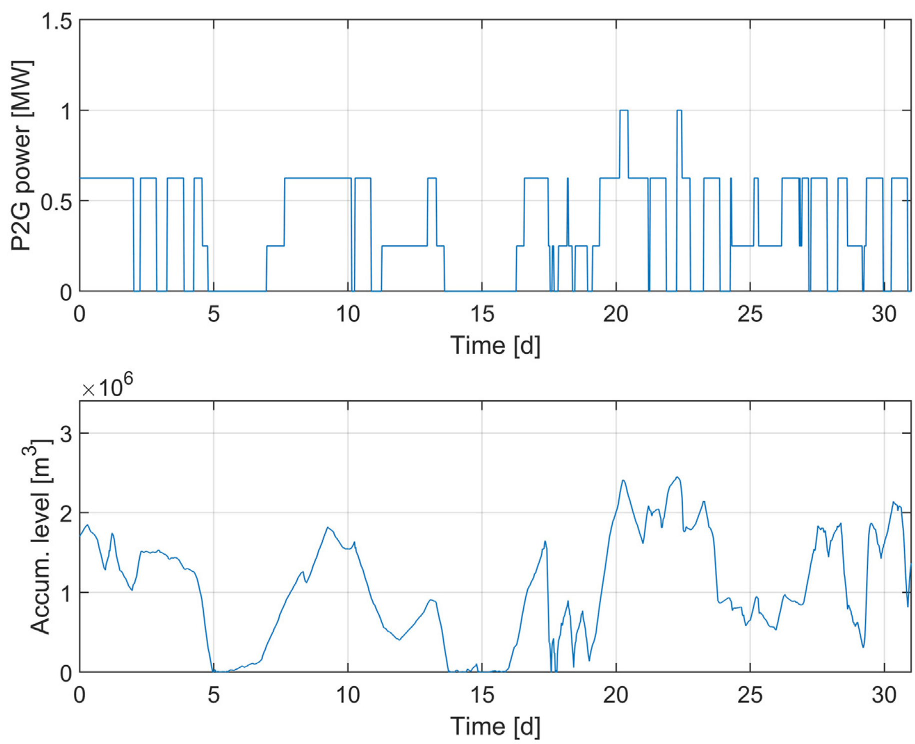

Fig. 14. Operation of a 1.25-MW electrolyser and water accumulation over a period of one month.

costs for the implementation of a 1-MW P2G system were reported in Ref. [19] and are listed in Table 2.

Using the data from Table 2, capital expenditure costs (CapEx) and operating costs (OpEx) for the 1-MW P2G system's installation and operation can be estimated. The CapEx is €2,200,000 and the OpEx is €110,000/year, where the OpEx is calculated as 5% of CapEx. The expected lifetime of the P2G system is estimated at 15 years.

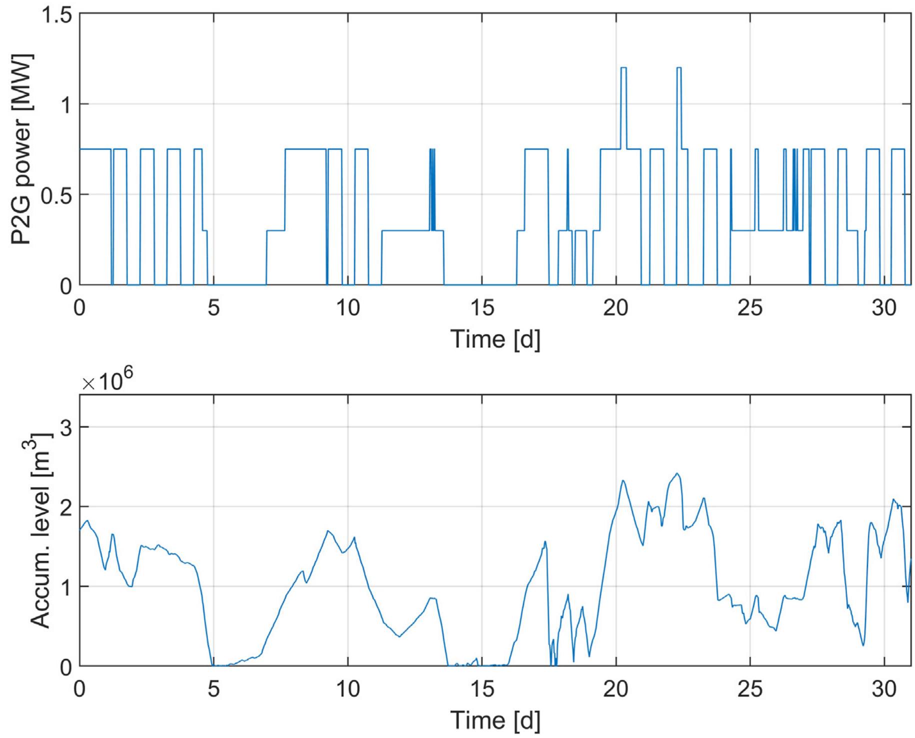

Fig. 15. Operation of a 1.5-MW electrolyser and water accumulation over a period of one month.

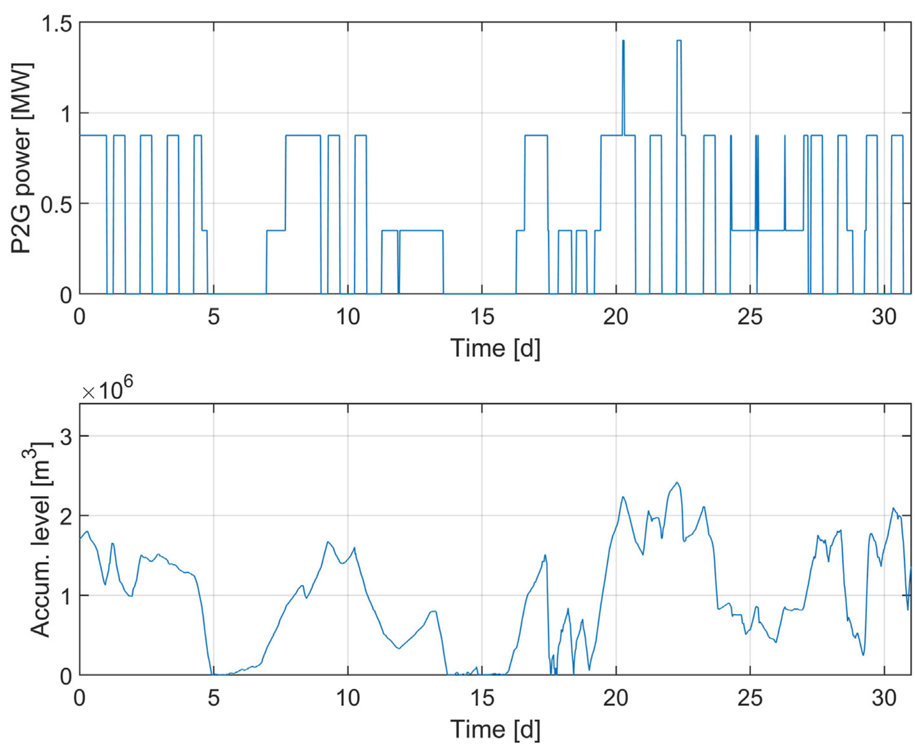

Fig. 16. Operation of a 1.75-MW electrolyser and water accumulation over a period of one month.

The cost of hydrogen production obtained from green electric energy and using a P2G system in the HPP consists of two parts:

- PC1 - CapEx and OpEx costs of the P2G system's equipment and maintenance,
- PC2 - cost of electric energy for P2G system operation.

Using the technical characteristics of the 1-MW P2G system, PC1 is calculated as

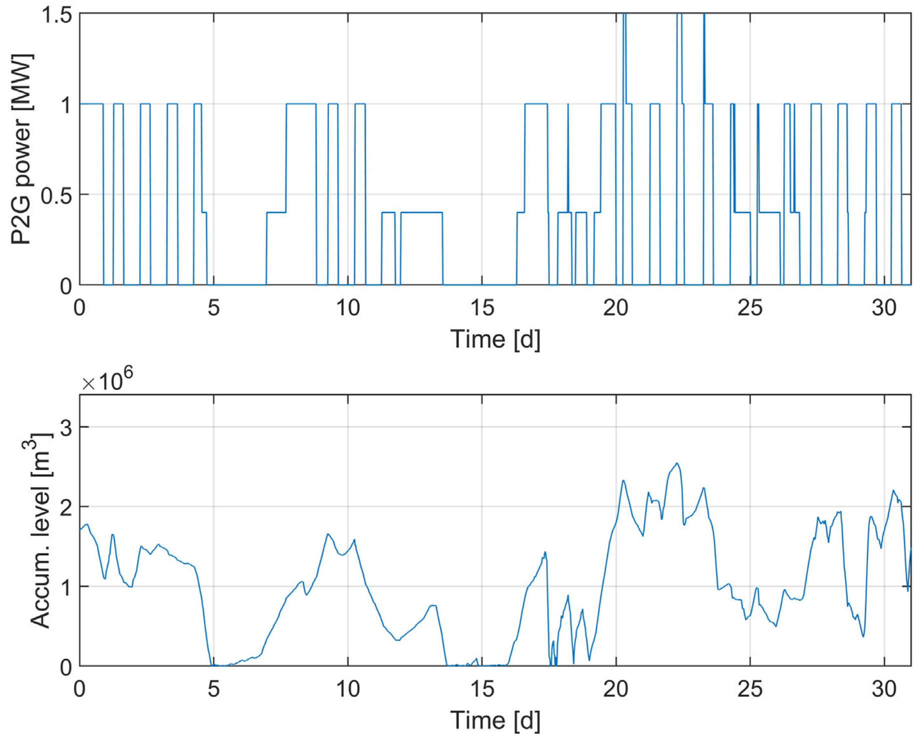

Fig. 17. Operation of a 2-MW electrolyser and water accumulation over a period of one month.

Table 1
Simulation results.

Electrolyser nominal power [MW]	Hydrogen produced [kg/month]	Energy for P2G operation [MWh/month]	Electrolyser's utilisation rate [%]	Number of Starts/shutdowns of P2G system [No./month]	Final pressure in H_2-storage tank [bar]
0.50	3653	184.6	49.6	5	113.6
0.75	4522	228.5	40.9	5	240.0
1.00	5058	255.6	33.0	12	335.4
1.25	5259	265.7	28.6	20	333.6
1.50	5385	272.1	24.4	21	338.3
1.75	5458	275.8	20.1	25	333.7
2.00	5512	278.5	18.7	25	334.7

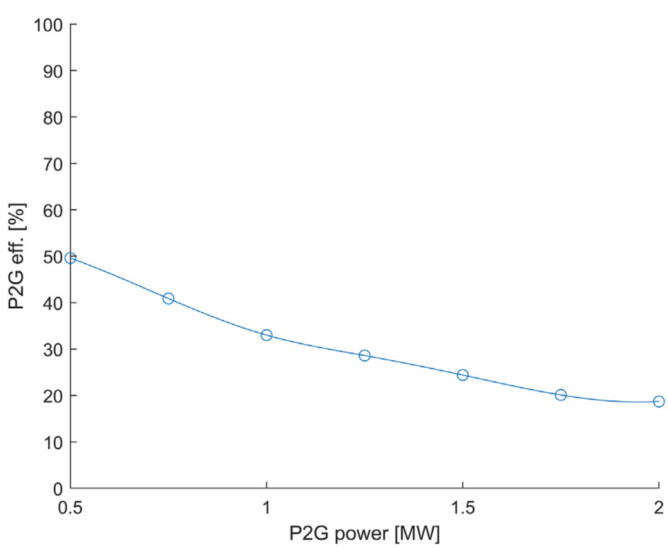

Fig. 18. Electrolyser's utilisation rate.

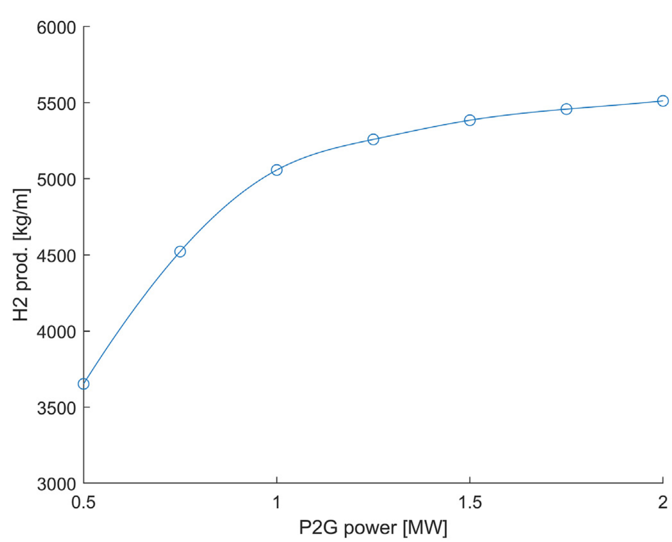

Fig. 19. Monthly amount of H_2 produced.

Table 2
Estimated costs of the components for a P2G system.

Main P2G System Implementation Costs	Estimated Cost [€]
Project documentation	100,000
Electrolyser	1,600,000
High-pressure storage	200,000
BoP[a] components	120,000
Electric connection to HPP	100,000
Construction and assembly works	80,000
Total costs	2,200,000

[a] BoP: various supporting and auxiliary components.

$$PC1\ (€\,/\,kg) = (CapEx + OpEx)\,/\,m_{(total)} \tag{1}$$

The numerator for the 1-MW electrolyser in Eq. (1) is calculated as

$$CapEx + OpEx = €2,200,000 + 15 \times €110,000 = €3,850,000 \tag{2}$$

or $€29.30/h$, and represents the cost of P2G system's installation, whether the system is operating or not.

The denominator from Eq. (1) depends on the actual hourly production of hydrogen. Under the assumption that the total hydrogen production during the 15-year lifetime of the P2G system is calculated as in Eq. (2) and that the system operates on average at 30% of its nominal capacity

$$m_{(total)} = 647\ kg\Big/day \times 365\ days\Big/year \times 15\ years \times 0.3 = 1,062,698\ kg \tag{3}$$

or 8.09 kg/h of hydrogen.

The calculated PC1 using Eqs. (1) and (3) equals €3.62/kg of hydrogen.

PC2 represents the cost of electrical energy used for the hydrogen production, Eq. (4).

$$PC2\ (€\,/\,kg) = cost\ of\ electric\ energy\ (€\,/\,kWh) \times P2G\ power\ consumption\ (kWh\,/\,kg). \tag{4}$$

In the case that the electricity for hydrogen production is generated from excess-water accumulation, PC2 is zero. However, if this energy could be otherwise sold on the electricity market, the price of the consumed electric energy for hydrogen production is not zero. Table 3 shows the structure of the hydrogen-production price for different electricity costs and for the assumed consumption of the electrolyser (rounded to 50 kWh/kg). In the EU's electricity market, the prices in the last decade vary around an average of €50/MWh [30], where the production price is around 30% lower. These assumptions have also been considered in a further analysis of the economic viability of hydrogen production in the case-study HPP, where it is assumed that 1 MWh of electrical energy can be sold on the electricity market for €50, while the production cost of electrical energy is €35/MWh.

Table 3
Hydrogen production cost in relation to the price for electrical energy.

Electricity costs [€/MWh]	PC1 [€/kg]	PC2 [€/kg]	PC[a] (Total) [€/kg]
0	3.62	0.00	3.62
35	3.62	1.75	5.37
50	3.62	2.50	6.12
120	3.62	6.00	9.62

[a] Production costs of hydrogen from Table 4 exclude value-added tax (VAT) and other charges.

4.4. Economic viability of hydrogen production in the HPP

In the case presented here, the HPP is contractually obliged on an annual basis to supply fixed-price electricity, regularly, according to the prescribed timetable and is not involved in a stock-exchange electricity market or ancillary services. Even in this case, the HPP can generate extra profit with additional hydrogen production, which is limited by the amount of excess hydropower.

Assuming that the HPP would have more options to deviate from the prescribed timetable, it would be interesting to know in which cases hydrogen production is more profitable than the production of electricity. For example, let us assume we have an electrolyser with a nominal power of 1 MW, an average load of 0.3, a selling price of €8/kg for hydrogen, and a selling price of €50/MWh for supplied electric energy production (see Table 4). An important quantity is the difference between the cash flow generated by hydrogen production and the cash flow generated by electrical energy. The cash-flow difference (profit) is expressed as

$$\text{Profit}\ (€\,/\,h) = Eff\_factor \times Power_{elect} \times \left(\frac{(Price_{H2sell} - Price_{H2prod})}{Cons_{H2}} - Price_{EE}\right). \tag{5}$$

For the above case, the profit from hydrogen generation versus electricity production turns positive with an extra profit of €11.28/h (see Fig. 20). With a market selling price for hydrogen of less than €6.12/kg, it makes more sense to produce additional electricity if we can sell it on the market for €50/MWh.

4.5. Use of produced green hydrogen

Fig. 19 shows that hydrogen cogeneration of about 5000 kg per month (around 160 kg/day) is possible. In an agreement with the HPP's nearby city administration, the green hydrogen produced will be used for some hydrogen-powered suburban buses.

City or suburban buses are very close to the ideal green-hydrogen application, i.e., buses that are refuelled at one or a few dedicated refuelling stations. This greatly reduces the costs of the hydrogen-refuelling infrastructure. For economic reasons, city buses must operate permanently, without long stops, so the possibility for rapid refuelling is very important. Most importantly, vehicles fuelled by green hydrogen have no emissions and generate much less noise than those internal combustion engines fuelled by hydrocarbons [31].

A hydrogen-driven bus of length 12 m has a hydrogen consumption of around 9 kg/100 km [32,33]. With an average travelling distance of 400 km/day, the daily production of green hydrogen in the case-study HPP could fuel four such buses per day.

Table 4
Variables and their assumed values.

Variable	Variable description	Assumed value
$Power_{elect}$	Nominal electric power used for hydrogen generation	1 MW
Eff_factor	Factor of exploitation of 1-MW electrolyser	0.3
$Price_{H2prod}$	Production price of hydrogen	€3.62/kg
$Price_{H2sell}$	Selling price of hydrogen	€8/kg
$Cons_{H2}$	P2G consumption of electricity per unit of mass of generated hydrogen	50 kWh/kg
$Price_{EE}$	Selling price of extra electric energy	€50/MWh

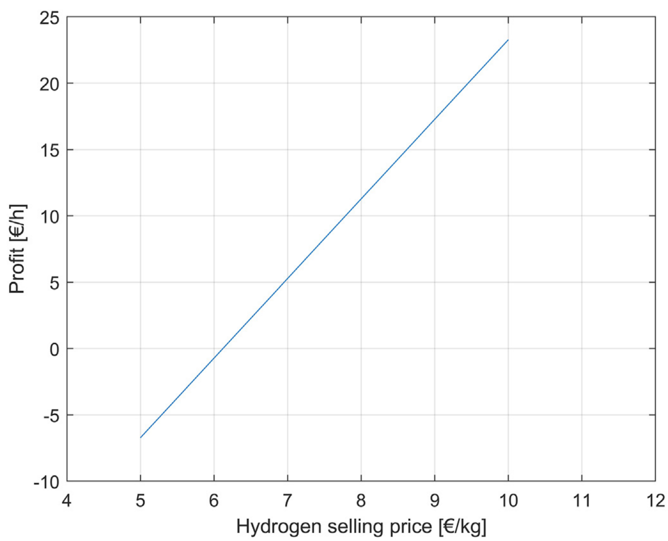

Fig. 20. Profit from hydrogen production vs. selling price for the stated case.

5. Inclusion of PV field

The management of the case-study HPP is aware of the advantages of higher hydrogen production while meeting the requirements for the electricity supply, and therefore intends to dedicate part of the energy obtained from the PV field to hydrogen production in the future. For example, the 6-MW PV field produces around 230 MWh of electricity per month (Fig. 21), which with the same configuration of the 1-MW P2G system, according to our developed model, gives a theoretical production of an additional amount of hydrogen up to 4600 kg/month.

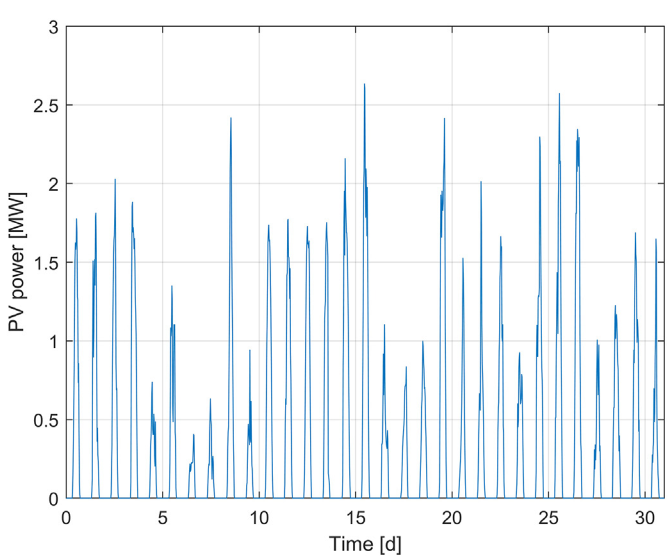

Fig. 21. Monthly production of electrical energy from 6-MW PV field (around 233 MWh, January 2019).

The simulation runs show that using part of the electricity from the PV field can produce up to 2500 kg more hydrogen per month, due to the limitations of the case-study HPP and the P2G system used (predefined timetable, 1-MW P2G system, H_2-storage capacity, simulated H_2 consumption). At the same time, the state of the water accumulation and the efficiency of the P2G system are improved (see Fig. 22).

6. Discussion

Today, it is possible to produce green hydrogen for the storage of surplus electricity, for use as a feedstock in various process industries, and as a clean fuel in the heating and transport sectors. Green hydrogen is thus crucial for cross-sectoral integration and to achieve the transition to a low-carbon society, an essential part of the European strategy to become carbon-neutral by 2050 [34]. Slovenia has not yet adopted a strategic plan for hydrogen, but there are already some initiatives [35,36] for hydrogen production and use. Another new initiative is presented in this article, with the aim of assessing the implementation costs of a P2G system for the cogeneration of a limited amount of green hydrogen in the case-study HPP during its regular operation with actual water inflows.

6.1. Utilisation of excess-water accumulation for cogeneration

We have shown that the cogeneration of green hydrogen from a hydropower surplus in the case-study HPP is possible while considering the predefined electricity-production timetable. The considered HPP has a specific location (the last in a chain of five run-of-river HPPs) and its water accumulation and the prescribed timetable depend on the operation of its predecessors along the chain of HPPs, but we believe that moderate hydrogen cogeneration is also possible in other, similar run-of-river HPPs. The reason for this is the ever-present discrepancy between the forecast and the actual situation. Namely, the timetable for the HPP is prepared by the operator of the electro-energetic system on the basis of models of the available production capacities, forecasted consumption, water accumulation, the state of river flows, weather forecasts and the system operator's strategy. The uncertainty in the model's input parameters is reflected in the output timetable for the individual HPP and, for this reason, a small reserve of water for potential exploitation is envisaged.

6.2. Increasing the profitability of the HPP's operation

The investment in cogeneration also makes sense from the point of view of the profitability of case-study HPP's operation. Today, the considered HPP earns its profit only from the yearly fixed-price contract with the Slovenian system operator and does not participate in daily trading between producers and consumers on the electric-energy stock exchange, nor is it involved in the provision of

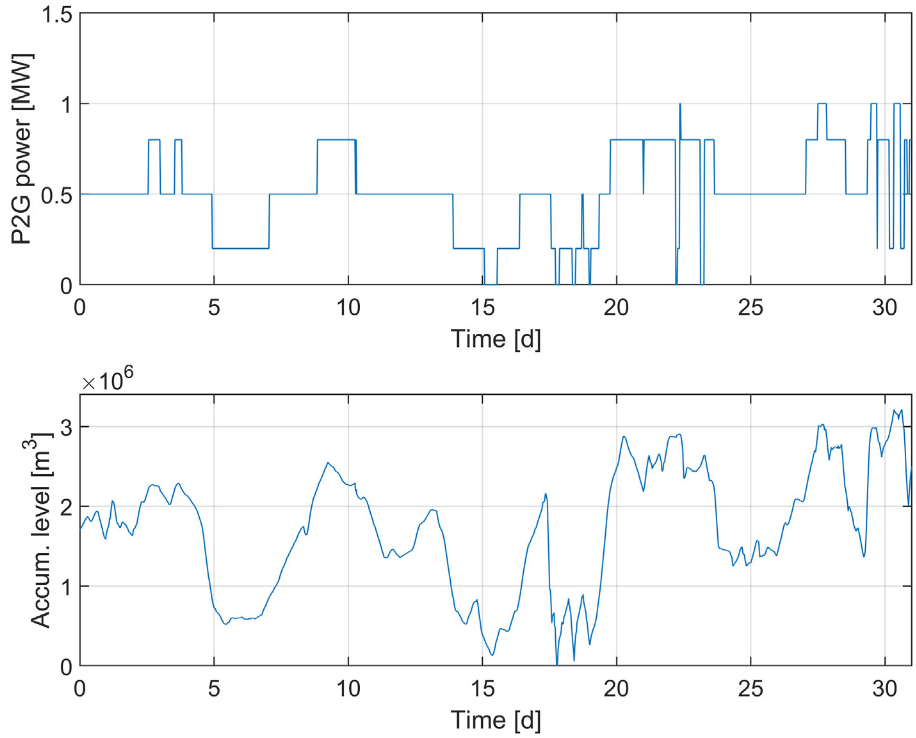

Fig. 22. Operation of a 1-MW electrolyser and water accumulation over a period of one month with additional electrical energy from the PV field. The Simulink scheme consists of the following modules.

ancillary services. Therefore, despite there being only moderate green-hydrogen production available, it can still contribute to higher revenues.

Assuming that the HPP produces around 7700 MWh of electricity per month according to the prescribed timetable, at a production price of €35/MWh and a sales price of €50/MWh, it will have a monthly profit of around €115,500. At the same time, it can produce up to 5000 kg of hydrogen from surplus hydropower every month, which, at a production price of €3.62/kg and an assumed selling price of €6/kg, means additional earnings of around €12,000/month.

The above assumptions might suffer from some inaccuracies due to the uncertain price situation on the global energy market in recent months. The next opportunity to increase the revenue is in the strategic decision of the management to enter the electric-energy stock exchange. In this case, a dilemma will arise as to how to delimit the volume of electricity and hydrogen production due to their current prices on the global market.

6.3. Use of the MATLAB/Simulink model

The developed MATLAB/Simulink model was effective for dimensioning the P2G system. It provides an important insight into the operational details and limitations of the P2G system's configuration.

Given the basic assumptions and limitations (Section 4.2), we selected an electrolyser with a nominal power of 1 MW. In the case-study HPP configuration it has a relatively low utilisation rate due to the requirements for (i) meeting the prescribed timetable, (ii) the limited capacity of hydrogen storage and (iii) the hydrogen-consumption profile. However, it was chosen by considering the planned PV field installation at the HPP's facilities, which will improve its capacity for electricity production.

The authors believe that at this stage a mathematical optimisation of the electrolyser's nominal power is not required, as there are several open issues (e.g., predicted hydrogen consumption, limitations regarding the commercial availability of the electrolyser and other components of the complete P2G system, the future strategy of the HPP's management) that need to be addressed with priority.

The model enables the verification of various operational scenarios for the case-study HPP, where its added benefit is an ability to estimate the financial revenues from both electricity and hydrogen production. In the case of a decision by the HPP's management to enter the energy stock exchange, the developed model can serve as a part of the decision-support system.

6.4. Inclusion of PV field

The PV field enables higher electricity and hydrogen production. The simulation runs show that the, e.g., 6-MW PV field produces at least 230 MWh (during winter months) of electricity per month, which gives a theoretical production of an additional 4600 kg/month of hydrogen. In reality, the actually additional production is up to 2500 kg more hydrogen per month, due to limitations imposed by the predefined timetable, the 1-MW electrolyser, the hydrogen-storage capacity and its simulated consumption. If we want to take full advantage of the PV field's potential, we will have to resize the P2G system. But even the existing configuration of the P2G system contributes to a higher utilisation rate for the electrolyser and the accumulated water.

The calculations show that despite the relatively high cost of installing a PV field (€700,000/MW) [37], hydrogen production is cost-effective at a price up to €6/kg and can contribute to a net profit for the case-study HPP.

6.5. Environmental issues

The harmonization of renewable energy production, environmental protection and production efficiency is a complex challenge

[38,39]. Therefore, we intend to focus a significant part of our future work on the planned construction of the PV field, where we will define its appropriate location by considering the possibilities for its spatial arrangement [40]. Using the developed HPP model we will examine different scenarios for the HPP's operation, where we will pay special attention to the required capacity of the P2G system for green-hydrogen production and upgrade the control algorithm for the use of additional energy from the PV field to reduce the oscillations in the water accumulation/denivelation range of the case-study HPP's water basin. Research shows [41] that in this way we can significantly improve environmental flow releases for the riverine ecosystem's needs.

7. Conclusions

The article addresses the idea of exploiting water reserves resulting from a mismatch between the daily required electricity production and the actual water inflow for green-hydrogen production. We have shown that in the case of the chosen Slovenian HPP this mismatch really exists and that it can be used for the cogeneration of green hydrogen. The techno-economic assessment also showed that the investment in the required P2G system's installation is economically viable and that at current energy prices it would lead to higher revenues for the HPP.

The article presents:

- the actual hydropower surplus in the case-study HPP that arises due to the mismatch between the daily predefined electricity production (timetable) and the actual water inflows,
- the design and implementation of the HPP model in the MATLAB/Simulink programming environment, which enables the verification of various operational scenarios of the case-study HPP,
- the design of a control algorithm for the P2G system that allows cogeneration of a smaller amount of green hydrogen during periods of excess water accumulation in the case-study HPP while meeting the prescribed timetable for electricity production,
- the estimation of the amount of green hydrogen that can be obtained from the existing hydropower surplus and the economic viability of green-hydrogen cogeneration.

Given the plant's operating limitations and the consequent moderate utilisation rate of the selected 1-MW electrolyser, the amount of green hydrogen produced is relatively low, but it can still be an important contribution to a larger revenue. It is shown that the utilisation rate of the chosen electrolyser can be significantly improved by extending the case-study HPP facilities with the planned PV field.

Slovenia is already running some initiatives for the production and use of green hydrogen. Based on a comparison of heating- and transport-fuel prices in Slovenia, green hydrogen is already competitive in the field of transport if its sales price is not burdened with additional environmental taxes, as is the case with other fuels [19]. Therefore, the plan is to use the produced green hydrogen from the case-study HPP first in local public transport in a nearby city, and in this way we will also contribute to a reduction in CO_2 emissions.

CRediT authorship contribution statement

David Jure Jovan: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Roles/Writing - original draft, Writing – review & editing. **Gregor Dolanc:** Formal analysis, Funding acquisition, Investigation, Supervision, Writing – review & editing. **Boštjan Pregelj:** Data curation, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could influence the work reported in this paper.

Acknowledgments

This work was supported by the research program P2-0001 and the project L2-1832, both financed by the Ministry of Education, Science and Sport of the Republic of Slovenia. The support of the ministry is gratefully acknowledged.

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