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Sizing of a hydrogen system for green-hydrogen production by utilising surplus water accumulation in a hydropower plant

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ABSTRACT

The utilisation of surplus hydro energy can enhance the profitability of hydropower plant operation by cogeneration of green hydrogen along regular electricity production. Effective integration of the hydrogen system requires its appropriate sizing based on surplus hydro energy availability, its temporal dynamics, scheduled electricity generation, and expected hydrogen demand. The article introduces a decision-support tool designed for the optimal sizing of hydrogen systems in run-of-river hydropower plants with surplus hydropower. In contrast to conventional methods, the developed tool enables rapid configuration of key hydrogen-system components without relying on complex optimisation algorithms. Implemented in MATLAB App Designer, the tool provides a visual inspection of the entire search space, thus avoiding possible sub-optimal solutions. The tool has been tested on the case-study hydropower plant and it demonstrates the capabilities for proper sizing of a hydrogen system. The results show that the hydrogen system with 0.75-MW electrolyser and 20 m^3 storage tank can generate up to 52,652 € in a rainy month and can produce up to 86 tonnes of hydrogen annually, achieving approximately 440,000 € of additional income. The tool can provide valuable insights into hydrogen system's installation profitability, to guide investment decisions in sustainable hydrogen infrastructure and can contribute to broader energy transition strategies.

1. Introduction

The world is grappling with increasing energy consumption, air pollution and climate changes. In response the European Union is actively reducing reliance on carbon-based fossil fuels and shifting towards renewable energy sources (RESs). Within these emerging electro-energetic systems that have a high share of RESs, hydrogen has surfaced as pivotal energy carrier that contributes to the storage and usage of surplus green energy and thus reduces air pollution, climate change and can be used as a feedstock in a variety of industrial processes. Green hydrogen produced from RESs is thus of growing significance. Hydropower plants (HPPs) are particularly well-suited for this task, as they are less sensitive to weather conditions compared to other RESs and can reliably cogenerate electricity and green hydrogen.

Green hydrogen has the potential to accelerate the process of scaling up clean and renewable energy deployment, but its integration into electrical power systems still remains under-studied [1]. However, research on the topic of using hydrogen-related technologies is intensified significantly, particularly during the last decade [2]. The authors in Ref. [3] consider that two basic approaches have the potential for green hydrogen production from hydropower. The first assumes that a certain part of the available hydropower potential is dedicated to the production of green hydrogen, while the alternative assumes the production of hydrogen on the basis of surpluses of hydropower, which arise from time to time for various reasons. Recent studies employing this second approach have shown that the hydrogen production from surplus hydropower meets the principles of the circular economy [4] and that is a significant opportunity for profit increase [5].

The usual way for green-hydrogen production in a HPP is the installation of a hydrogen system (HS), which consists of an electrolyser, a hydrogen storage tank and additional necessary process equipment [6]. The capacity of such a HS must be adjusted to the available surplus of hydro energy, its dynamics and the expected volume of the produced hydrogen consumption. Despite the indisputable advantages of using green hydrogen in various fields, the technological feasibility of HSs, and above all their economic viability, still remain open issues. In general, the capital and operating costs (CapEx, OpEx) of HS components increase with their sizes and capacities. For this reason, costs must to be

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minimised since they directly affect the hydrogen production costs and the financial sustainability of the HS. The most appropriate way to this goal is the appropriate dimensioning of HS assemblies.

As emphasised in Ref. [7], planning, placement, design, sizing and control are the most critical optimisation objectives in developing reliable, cost-effective, and sustainable energy solutions, particularly in off-grid and renewable-integrated contexts. Since the main focus of this article is on proper sizing and control of a HS within a HPP, the literature survey is restricted to these aspects.

Sizing of HS refers to selecting appropriate types and sizes of the system components. In the case of HSs, particular attention must be given to the electrolyser and hydrogen storage system, both central to system performance. Typically, capital and operating costs (CapEx, OpEx) rise with component size. Therefore, minimising these costs is essential to ensure the economic sustainability of HSs and the broader HS configuration.

Numerous studies over the past decade have investigated the optimal sizing of hybrid systems, many of which incorporate techno-economic issues during the design phase. According to Ref. [8], integrating a HS into a wind plant or HPP significantly enhances its economic feasibility. The economic analysis in Ref. [9] similarly supports the view that green hydrogen will become a viable decarbonisation strategy for industry, particularly where carbon pricing mechanisms are introduced and equipment costs decline. Reference [10] echoes this sentiment, noting growing interest from investors and policymakers, though acknowledging that cost competitiveness remains a significant barrier.

Over-sizing leads to high upfront costs and under-utilisation of equipment, while under-sizing may result in operational constraints. Consequently, optimal sizing has emerged as a key research priority. In Ref. [11], four sizing methods for a stand-alone hybrid generation system, integrating renewable energy sources such as photovoltaic panels and wind turbine, along with a storage system based on battery and hydrogen (including fuel cell, electrolyser and hydrogen-storage tank), are described. The first method relies on basic equations for sizing, while the second achieve optimal technical sizing through Simulink Design Optimisation. The remaining two methods utilise the hybrid-system optimisation software HOMER and HOGA to perform optimal techno-economical sizing. A MATLAB/Simulink model was used to simulate the annual performance of the system designed using each approach. Supporting this methodology, the authors in Refs. [12,13] suggest that commercial optimisation software such as HOMER Pro or HOGA is commonly used; however, they also highlight that such tools may limit model customisation due to their inherent constraints. Consequently, some researchers opt for more flexible, general modelling methods. In this context, the authors in Ref. [14] provide a comprehensive list of optimisation techniques used for equipment sizing and point out limitations of HOMER software, including its black-box nature, platform dependency, and inflexibility in applying diverse optimisation strategies. To address these shortcomings, modern artificial intelligence methods have been proposed, with particle-swarm-optimisation (PSO) method standing out as a particularly promising approach. As shown in Ref. [15], PSO demonstrates high speed and accuracy in identifying optimal design parameters, making it an effective solution for complex hybrid system sizing challenges.

In [16], the authors evaluate the performance of seven different algorithms for optimum sizing of a hybrid system to continuously satisfy the load demand with the minimal total annual costs. Among these algorithms, three well-known heuristic algorithms, namely, PSO, tabu search and simulated annealing, and four recently improved meta-heuristic algorithms, namely, improved PSO, improved harmony search, improved harmony-search-based simulated annealing, and artificial bee-swarm optimisation, are applied to the system and the results are compared in context of the total operating costs. The article finds that from the optimisation viewpoint, the artificial bee-swarm optimisation method yields more promising results than the other algorithms and it is also the most robust.

Beyond technical and economic objectives [17], argues that multi-objective optimisation should incorporate criteria such as air pollution reduction, system reliability, customer satisfaction, and minimisation of surplus energy. The paper presents a comprehensive survey on objective functions, constraints, and decision variables in hybrid-system design, noting that emerging metrics such as grid dependency and end-user satisfaction warrant further exploration.

In addition to sizing, effective control strategies are fundamental to the reliable operation of hybrid systems. Reference [18] proposes three control approaches based on system operating modes, balancing load demand fulfilment, hydrogen tank management, and battery lifecycle optimisation, while also addressing techno-economic factors. Another control method, outlined in Ref. [19] uses a power-decoupling strategy to coordinate energy sources, ensuring fast and effective energy delivery while preserving system integrity. An autonomous control strategy is presented in Ref. [20] focusing on hydrogen production powered by a photovoltaic array and alkaline electrolyser. The proposed controller uses hybrid control theory to manage the system's nonlinear dynamics, optimise solar energy capture, and respect electrolyser constraints.

Control of grid-connected hybrid systems is another active research area. In Ref. [21] the authors develop a simplified dynamic model for a grid-assisted solar-HS, using the electrolyser current as a control variable. The proposed strategy aims to minimise grid energy consumption under variable solar input, while accommodating the physical limitations of hydrogen storage, resulting in a non-smooth, discontinuous optimisation problem. Reference [22] underlines the importance of variable-power electrolyser operation, suggesting higher activation thresholds based on system constraints. The study advocates for integrated techno-economic optimisation encompassing both system design and control strategy. Similarly [23], explores how hydrogen producers can maximise profitability through optimal interaction with both electricity and hydrogen markets, considering offtake agreements and distribution options under market variability.

A recent review in Ref. [24] provides a comprehensive overview of control challenges in hydrogen energy storage systems, particularly their integration into modern power grids. The authors highlight the complexity of managing intermittency, system dynamics, and market interactions in such configurations.

The concept of cogeneration of hydrogen from surplus hydropower has long been recognised. Several real-world initiatives demonstrate the feasibility of green hydrogen production from hydropower:

- *An up-to-date overview* [25] *of global trends in green hydrogen production, with a focus on leaders in the field including Australia, the European Union, India, the USA, China, Canada, Japan, South Korea, and North Africa.*
- *Gösgen HPP, Switzerland: Produces 300 tonnes of hydrogen annually, powering up to 50 trucks or 1700 cars* [26].
- *Reichenau HPP, Switzerland: A 2.*5 MW *facility under construction, expected to produce 350 tonnes annually* [27].
- *Ljósifoss Station, Iceland: Designed for phased hydrogen production to support Reykjavík's public transport* [28].
- *Hydro-Québec, Canada: Collaborating with ThyssenKrupp on an* 88-MW *electrolysis plant to produce 11,100 tonnes annually for biofuel applications* [29,30].

Despite the progress described above *the key research gaps and objectives identified are summarised as follows:*

- *Integration of hydrogen systems into hydropower plants is under-researched, especially regarding surplus energy use.*
- *Economic feasibility and optimal sizing of hydrogen components (electrolysers, storage) are* not yet receiving enough attention.
- *Coordination between hydrogen production and regular HPP operations lacks effective control strategies.*

- *Current tools for techno-economic assessment are limited, requiring practical, simulation-based support systems.*
- *A need exists for real-world validation using historical data to optimise hydrogen system performance and profitability.*

Addressing these gaps, the main research contribution of our work is investigation of both: the technical and the economic aspects of the integration of a HS into the operation of a HPP. The investigation is founded on a realistic model of an existing HPP and year-long operational data. It is extended with models of HS and PV field. The analysis encompasses electricity and hydrogen prices and consumption profiles as well as HS controls.

The results confirm that profitability of the cogeneration of electricity and green hydrogen in a HPP can be significantly improved by optimal sizing of the components of the HS, taking into account the expected demand for hydrogen and available electrical energy.

The remainder of the manuscript is structured as follows. Chapter 2 describes the methodology. Chapter 3 presents a mathematical model of the complete HPP system. This model, combined with a newly developed decision-support tool introduced in Chapter 4, is used to simulate HPP operations and optimally size equipment for green hydrogen cogeneration before implementation. Chapters 5 and 6 apply both the model and tool to a case-study HPP. Chapter 7 focuses on hydrogen system sizing, while Chapter 8 presents the results and discussion. The article concludes with key contributions, conclusions, and future work guidelines.

2. Methodology

To tackle the challenging task, the following methodology has been pursued. First, the model operation scope was determined and the time precision requirements. The following step was obtaining and organising operational data of the case-study HPP from its SCADA database for a period of one year. Next, the model configuration was determined (see Fig. 1) and physical process and economic models were implemented. Further, the HS's control system used to manage electrolyser power in relation to surplus of hydro energy was designed. Finally, a graphical interface was developed to display results.

All model components were then integrated into decision-support tool within the MATLAB/Simulink environment, in the article referred to as the *Hydrogen-System-Configuration Explorer* (HSCE). The HSCE was then used in a number of simulations using real data to identify the optimal HS main components configuration (electrolyser, hydrogen storage tank) for utilising surplus hydro energy for hydrogen cogeneration during the HPP regular operation.

The article's key novelty is the implementation of a decision-support tool that enables profound insight into optimal sizing of the HS in a HPP with available surplus hydropower for the cogeneration of electricity and hydrogen. This tool enables the evaluation of the economic viability of specific HPP–HS configurations and supports scenario-based analyses of system operation under varying conditions (e.g., seasonal variations such as winter and summer, prolonged drought or heavy rainfall, and daily demand fluctuations). The presented tool can assist with HS design and a techno-economic evaluation of its operation before any implementation. Innovations in decision-support tools, such as the application of HSCE, presented in the article, enable more accurate sizing of critical

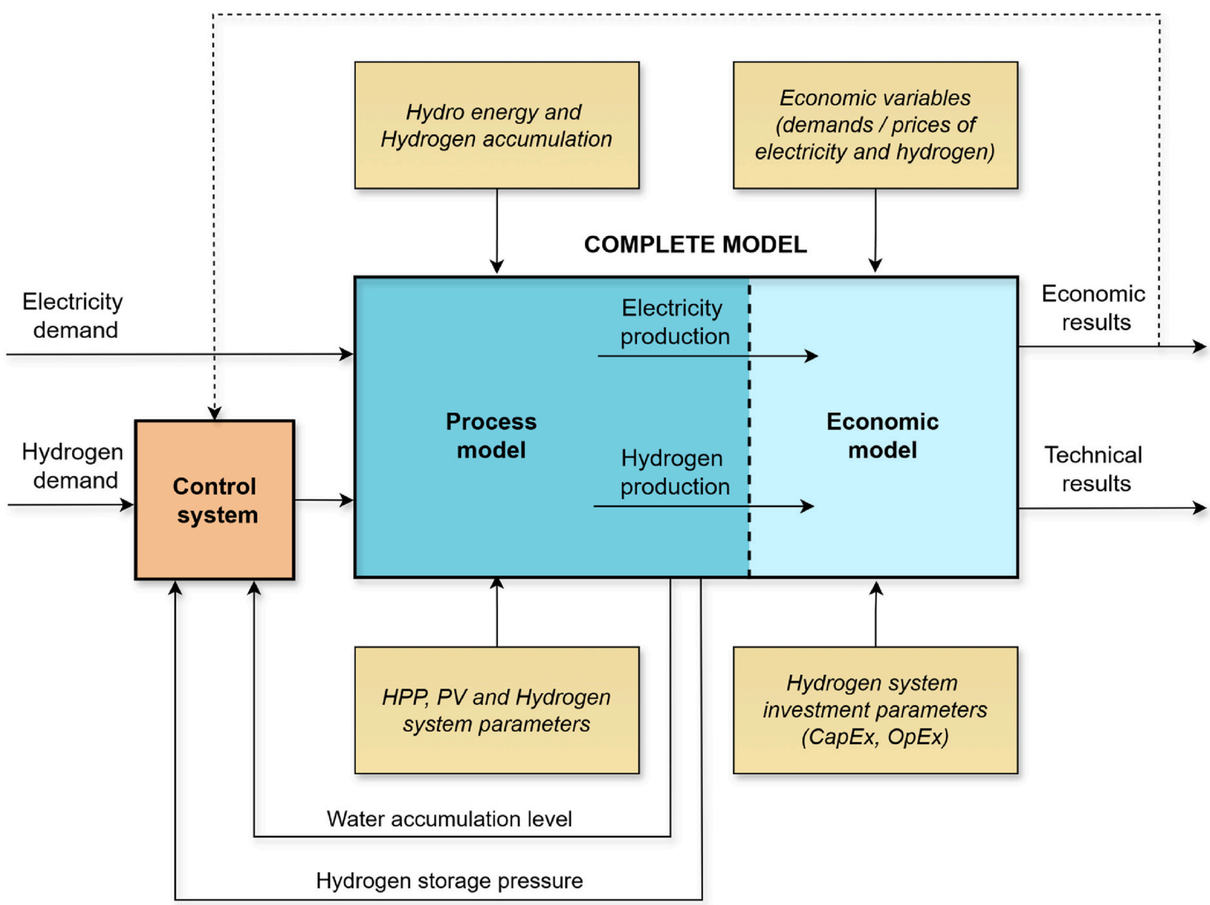

Fig. 1. Conceptual scheme of the developed system model with block colours (blue: process model, light-blue: economic model, brown: control system, beige: system parameters) aligned with MATLAB/Simulink model in Fig. 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

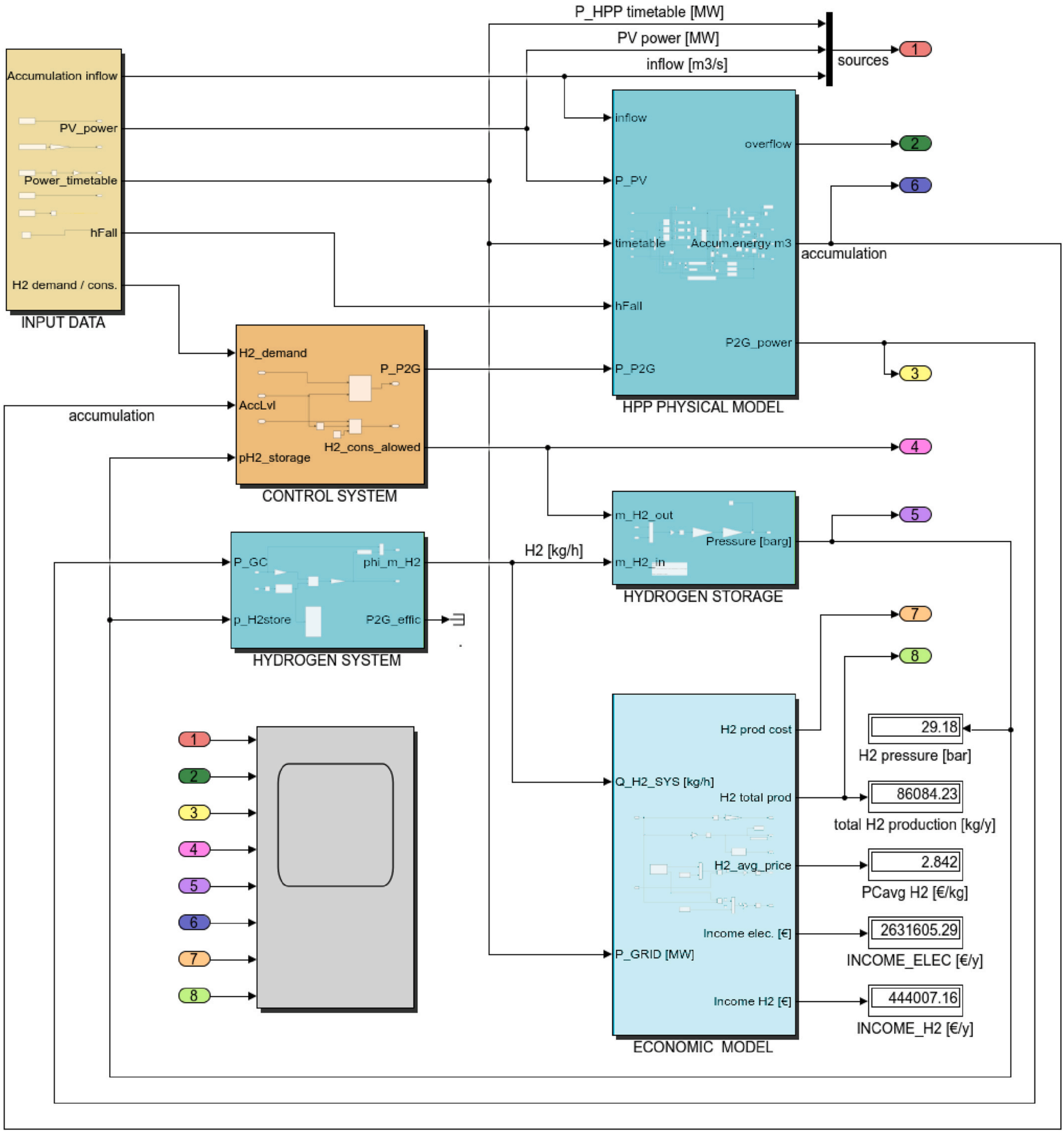

Fig. 2. Complete system model implemented in MATLAB/Simulink with functional blocks, colour-coded as in Fig. 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

HS components like electrolysers and hydrogen storage. By addressing technical, economic, and environmental challenges, the developed tool thus provides a pathway for more effective deployment of HSs.

3. The system model

The complete model was developed to allow simulation the operation of the HPP over the desired time interval and to evaluate the techno-economic effects of its operation. The developed model, consisting of a combination of first principle and data driven sub-models, was used in series of simulation experiments in which we have realistically assessed the idea of cogeneration by using real data on the case-study HPP's operating conditions, electrical energy and hydrogen-production requirements, their current market prices and some additional parameters (see Fig. 2).

The complete structure of the developed system model follows the structure of the process and consists of the following sub-models/modules:

- *The* ***input data*** *module uses historical data and generates real data on water inflow and outflow (available head) as function of time during a year, which are adjusted for further use.* The past data usually has a non-uniform format and time resolution (sampling time). One task of the input-data module is therefore to standardise the format and time resolution of the data through normalisation, resampling, interpolation and extrapolation. *It also provides the HPP's timetable tracking as defined by the electricity-grid operator. Analysis of historical data further enable the generation of weather and price predictions, incorporating stochastic noise to reflect decreasing trust levels over the coming days.*
- *The* ***process model*** *(HPP model) comprises mathematical sub-models representing the HPP physical model, including accumulation (reservoir), and the HS, which encompasses compression and storage. Simplifications are applied to reflect the dominant time dynamics of key variables. For example, the HPP is represented by a nonlinear turbine-generator model with first-order dynamics, which can be scaled to represent different power plant configurations. The accumulation sub-model includes parameters such as head drop, operating variation of water level (denivelation) and embankment slope. The electrolyser is modelled using a nonlinear lumped model based on manufacturer data. Hydrogen storage is also modelled, including compression losses. The parameters used in the case study are presented in Chapter 6.*
- *The* ***economic model*** *calculates the financial variables of the operation of the HPP and the hydrogen production by the HS. The financial flows are calculated using the quantities and prices of the electrical energy and hydrogen produced, as well as the capital and expenditure costs associated with financing and operating the plant.*
- *The* ***control system*** *module is an important part of the process, as it is designed to balance the requests for predicted electricity and hydrogen production (load-following). It takes into account the demand for electrical energy and hydrogen on the market, the available hydropower (water flow in the accumulation) and the constraints of the HPP (timetable, denivelation), the electrolyser (nominal power, continuous operation with minimal start-ups and shutdowns)* and the state of charge of the hydrogen storage (fulness, pressure). Due to limited space the weather and price forecasts are not used in the simulations.

The model adjustments to the presented case study are given in Chapter 6, while a comprehensive description of the model and its components can be found in Refs. [31,32], as the level of the detail required exceeds the scope of this article.

4. Hydrogen-System-Configuration Explorer

In order to determine the optimal HS's configuration for hydrogen production from surplus hydro energy we have developed a dedicated graphical decision-support tool in the *MATLAB/Simulink* environment, here named *Hydrogen-System-Configuration Explorer* (HSCE). It assists the design and optimal sizing of the HS before its actual implementation and identifies the set of system parameters, that provide the best result according to a selected criterion function (CF). In general, the criteria can be one of the typical key performance indicators, such as profitability, total amount of produced hydrogen, hydrogen-production cost, HS's utilisation rate, etc. The idea and principle are represented in Fig. 3.

The key idea is to use "exhaustive", also called "brute force" optimisation. It is best used when the search space is small, optimality is critical, or for validating other algorithms. For optimisation problems with a small number of parameters, it enables a shorter time to find the optimal solution compared to iterative mathematical optimisation algorithms. In combination with a suitable graphical interface, it also enables a visual inspection of the entire search space, thus avoiding possible sub-optimal solutions.

In our case this means that the HS parameters that are the subject of optimisation had been chosen and then the HS operation by using the developed model is simulated at all possible combinations of its parameters inside the predefined search space. During each simulation

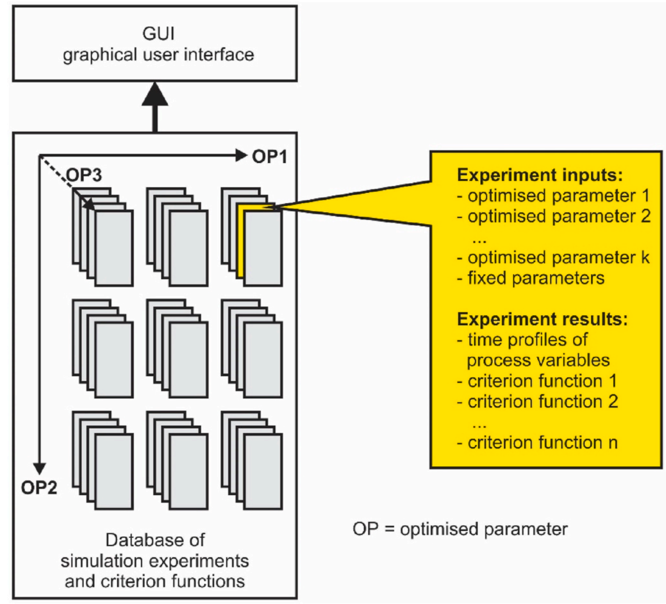

Fig. 3. Hydrogen-system-configuration explorer.

run, a set of results of the chosen criteria are recalculated. Given the relatively manageable scale of the problem and the critical impact of optimal parameter combinations on overall system performance, an exhaustive approach allowed us to evaluate all feasible scenarios systematically. This provided a clear benchmark for comparing other heuristic or stochastic methods and helped validate the robustness and sensitivity of our results.

The developed HSCE supports a sensitivity analysis, which shows how much and in which way and direction a particular optimised parameter affects the selected criteria. The HSCE contains two key features, which are crucial for an efficient and rapid sensitivity analysis:

- *Formation of a database of performed simulation experiments and belonging criterion functions, evaluated during each simulation run. Thanks to the database of performed experiments, a quick overview of different parameter combinations is possible, without the need for an online simulation, which can be time consuming.*
- *A graphical user interface (GUI) which provides the possibility for a graphical representation of the dependence between the selected criteria results and system parameters* (OPs) that are the subject of the optimisation. *The* GUI was designed using *MATLAB application designer* (*plotApp*, [33]). *This makes the sensitivity analysis very interactive, transparent, didactic and intuitive.* Additional *MATLAB* function "*parsim*" is used in the script, as it is useful to simulate a dynamic system multiple times in parallel.

To optimise a HS design, the most important parameters that are subject of optimisation within predefined scale and fragmentation are (i) OP1-nominal power of the HS's electrolyser and (ii) OP2-volume of the hydrogen storage tank. In the special case, when the HPP has an additional source of electricity in the form of a PV field, which is dedicated to the production of hydrogen, the nominal capacity of the PV field can also be included in the optimisation process as OP3.

An additional input to HSCE is also the desired daily hydrogen production. Here we must take into account that the priority of HPP operation is the production of electricity according to the timetable and that the amount of hydrogen produced is only possible from surplus water energy (and possibly PV fields).

The results of each simulation run are (i) time profiles of all process variables (mass-flow rates, energy flows, financial flows) and (ii) results of different criterion functions calculated in each simulation run: the amount of hydrogen produced, the hydrogen-production costs, the HS utilisation rate and the income from hydrogen production.

5. Application of HSCE at case-study HPP

The developed HSCE is used for parameter identification of optimal HS components in the selected case-study HPP. The HSCE enables (i) calculation of important key performance indicators related to HS installation, such as profitability, total amount of produced hydrogen, hydrogen-production cost, HS utilisation rate and (ii) proper sizing of a HS with taking into account all operational inputs and constraints of the case-study HPP.

The case-study HPP is a conventional run-of-river type HPP located as the last HPP in a cascade of five HPPs with a low-capacity water reservoir (see Fig. 4). Run-of-river HPPs with storage are said to have "pondage" which allows short-term water storage (hourly or daily). They are characterised as stable and reliable sources of electrical energy. Leveraging their consistent water flow, these plants can offer an opportunity for green-hydrogen production during regular operation, considering the fact that HPPs are feasible for providing surplus and dispatchable electricity to produce it [34].

The theoretical annual production of the case-study HPP is around 415 GWh, while the actual average production power is around 168 GWh, when operating with average power of 20.03 MW, due to the limitations in seasonal river water flow.

The main technical characteristics of the case-study HPP are given in Table 1.

The case-study HPP is also upgraded with a PV field with a nominal power of 6 MW (see Fig. 5). Part of this additional energy can be used for hydrogen production. An additional advantage of the case-study HPP is its location; namely, it is located near two towns with a total population of 15,000 people and near a highway. So, hydrogen could potentially be delivered to both cities and along the highway.

6. Model adjustment to case-study HPP

For tuning the model and for intended experimentation, real data from the case-study HPP were acquired and transformed into a form suitable for use in the simulation environment. Using this data, the model parameters of first principle and data-driven models were identified. Due to limited space only brief description of key sub-models is given in following, while the comprehensive description of all components is given in Ref. [31].

Table 1
Basic technical characteristics of the case-study HPP [35,36].

HPP data	Values
Number of generating units	3
Turbine type	Double-regulated vertical Kaplan turbine
Installed plant capacity (P_{HPP})	47.4 MW (3 · 15.8 MW)
Rated plant discharge	500 m^3/s
HPP low-water point (h_{LWL})	139 m.a.s.l.
Rated head (h)	14 m
Average annual output	168 GWh
Maximum upper water level (h_{UVL_MAX})	153 m.a.s.l.
Maximum operating variation of water level (d_{MAX})	1.1 m
Mean annual discharge	207 m^3/s
Reservoir capacity	19,300,000 m^3
Reservoir live storage (V_{ACUUM_MAX})	3,400,000 m^3
Number of spillways	5

6.1. Case study HPP data

Key steps in data preparation included collecting, cleaning and labelling the raw data in a unified form. First, the historical data from the HPP monitoring system were obtained, originally containing over 100 measured variables. From these, only the data representative of the modelled process (e.g., turbine flows, generator power output, set points such as the HPP operational timetable, water head and accumulation water level, etc.) were extracted. The direct measurements of water accumulation inflow were not available. Instead, they were estimated from the outflow from the upstream HPP using time-delay and smoothing filter, and then corrected for water evaporation and precipitation in the area between the two plants. Furthermore, the data were resampled and aligned to uniformly spaced 30-min intervals allowing simulations with arbitrary start date and duration. The described data pre-processing as well as subsequent simulations employing variable integration step and automatic selection of integration method was implemented within the MATLAB/Simulink programming environment.

The annual dynamics of the HPP's electrical energy production according to the timetable is shown in Fig. 6 with the annual average of 20.03 MW.

Another important information for further investigations is the change in water level of the reservoir (denivelation). The annual denivelation (d) regime is shown in Fig. 7. During normal HPP operation, the maximum-allowed denivelation is 1.1 m. Therefore, the actual level varies between 153 and 151.9 m.a.s.l.

Fig. 4. Case-study HPP [35].

Fig. 5. Case-study HPP's PV field [37].

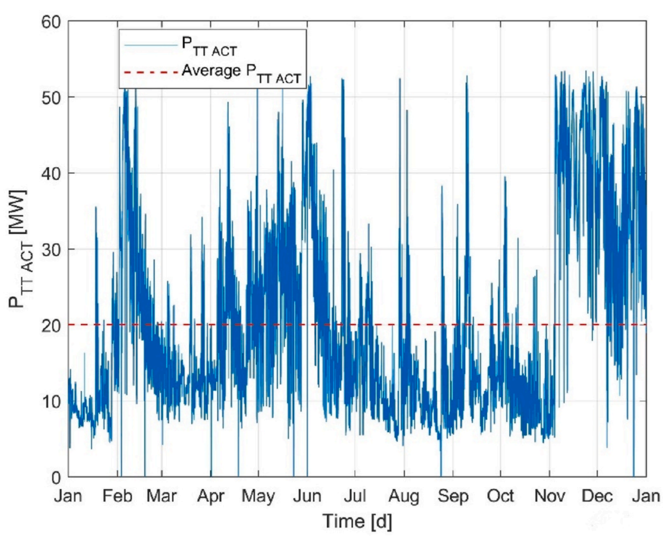

Fig. 6. Annual HPP timetable (P_{TT_ACT}).

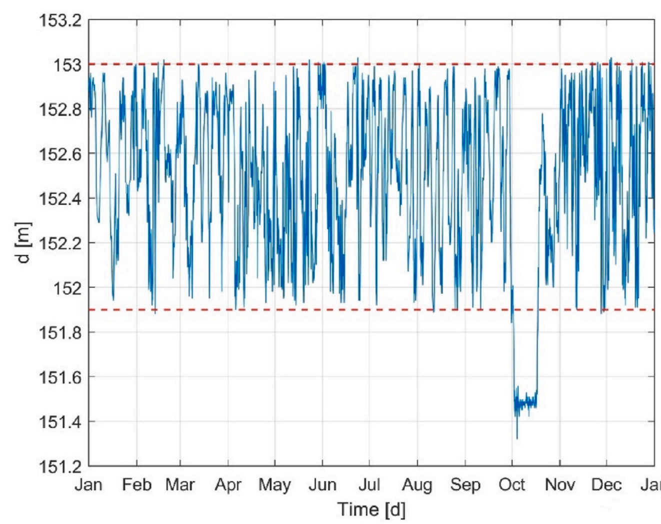

Fig. 7. HPP annual water reservoir denivelation (d). In the first half of October, the denivelation data are not relevant due to maintenance procedures on one of the three plant generating units.

Finally, to evaluate the amount of additional electrical energy obtained from the PV field, coupled to the case-study HPP, the historical solar irradiation data at the location of the PV field were obtained (see Fig. 8).

6.2. Turbine generator operation

The case-study HPP can operate with up to three turbine-generators at the same time. Each generator has the same nominal electrical power and can be controlled individually in order to adjust the production of the HPP to the demands. Parabolic turbine-generator efficiency curve dictates managed operation to maximise the overall efficiency. Thus, the generators are switched on gradually depending on the required power and is modelled as shown in Fig. 9.

The developed HPP model (see Fig. 10) is composed of two parts: (i, blue) power generation part comprises three (3) identical static nonlinear relations modelling turbine power generation [38], including the above-mentioned specific generator operation model, and (ii, green) the water accumulation model based on a trapezoid-shaped cross--section, with integrated bypass flow as well as flow-dependent denivelation curve.

6.3. Hydrogen generation, compression and storage model

The considered hydrogen system comprises electrolysis, hydrogen compression and storage. The dominant time constants are significantly shorter than 30-min sampling time, therefore lumped models are used. The *electrolysis* is modelled using nonlinear efficiency curve taken from provider data for its PEM electrolyser. The *hydrogen compression losses* are modelled using nonlinear characteristics as a function of hydrogen storage pressure and mass flow.

6.4. Hydrogen consumption

There was no information on hydrogen consumption for the case-study HPP and it had to be assumed for simulation. In agreement with local authorities, we proposed the use of cogenerated green hydrogen to fuel city buses powered by hydrogen fuel cells—an almost ideal application: (i) since buses are refuelled at centralised stations, the infrastructure costs are minimised, and (ii) buses require rapid refuelling due to continuous operation, suiting the hydrogen case.

With an average driving distance of around 400 km per day,

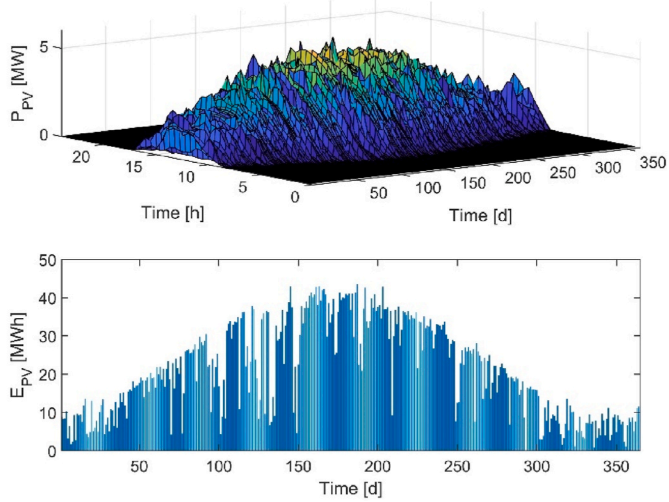

Fig. 8. Simulated annual production of electrical energy from 6-MW PV field.

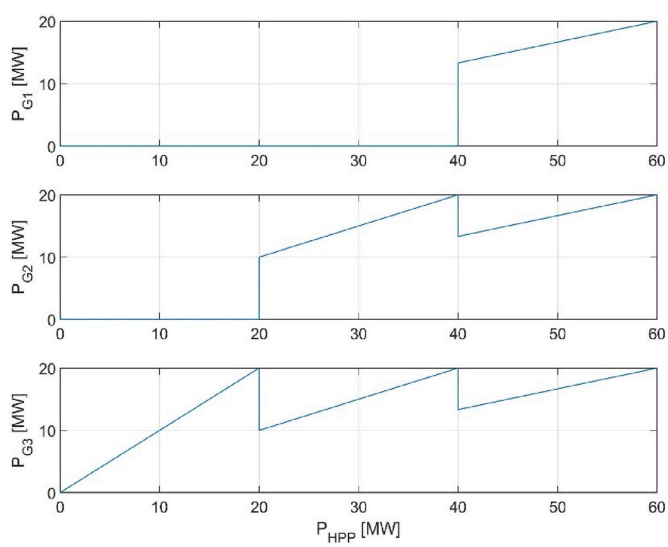

Fig. 9. Power-demand based operation model of generators G1, G2 and G3.

approximately 40 kg of hydrogen is needed for one bus out of the planned four every day. It is assumed that all buses are refuelled in the period 6–10 a.m. This means that the total daily hydrogen consumption only occurs in this period, which is a greater challenge from the point of view of dimensioning the HS and operating its control system than in the case of a more even daily hydrogen consumption.

The hydrogen production cost has a decisive influence on the economic viability of green hydrogen production in the case-study HPP. The economic model assumes HS in the case-study HPP that includes up to 1-MW electrolyser, a hydrogen storage system with up to 80 m^3 of volume and associated BOP equipment. The investment costs (CapEx) and operating costs (OpEx) for similar HS were elaborated in our previous article [39] and amount for CapEx to 2,200,000 €. Since the exact OpEx costs are difficult to predict it is assumed that these annual costs amount to 5 % of the CapEx costs, which means 110,000 €/year.

6.5. HS control system

A simple control algorithm in the form of the look-up table (see Table 2) was developed to determine the electric power available for hydrogen generation with respect to prescribed electricity generation (timetable), actual water conditions of the HPP and current state of a HS. The control algorithm calculates the factor f_L, which defines the proportion of the electrolyser's nominal electrical power to be used for hydrogen generation at any given time. The current factor (f_L) value is based on two key variables: (i) the available surplus of water in accumulation, represented by the percentage of the current state of charge in water reservoir (SoC_W) above the minimal allowed denivelation in the basin, and (ii) the percentage of the maximal hydrogen pressure in the storage tank, denoted as (p_{H2}). These variables reflect the balance between capacity of the HPP to divert excess water for hydrogen generation and the available storage capacity for the generated hydrogen.

The implemented look-up table defines pre-set responses of (f_L) for various combinations of (SoC_W) and (p_{H2}), ensuring that hydrogen generation remains within economical (electrolyser's efficiency is optimal within 20–80 % of its nominal power), safe and pressure-compliant operational limits. Specifically, the algorithm also does not allow surpassing the maximum tank pressure (p_{H2_MAX}), ensuring system integrity and safety. A solution with a simple look-up table was selected rather than more sophisticated control methods because the dynamics of the system are inherently slow. The rate of change in both water availability and hydrogen storage pressure is gradual, allowing the system to operate effectively without the need for more advanced control techniques. The simplicity of the look-up table not only fulfils the control requirements but also enhances robustness and ease of implementation.

7. Sizing of a hydrogen system for the case-study HPP

The basic reason for the sizing of HS's equipment is the minimisation of hydrogen-production costs and maximisation of income from hydrogen production and utilisation rate of the installed HS. To ensure appropriate sizing of the HS's main components, the following conditions have been taken into account: (i) the costs of the components of a HS, particularly the electrolyser and hydrogen storage, (ii) the availability of surplus electricity, from hydro and/or from the PV field, and (iii) the market selling price of both electricity and hydrogen; and predicted amount and dynamics of hydrogen consumption.

In presented case, three parameters are the subject of change and optimisation (listed in Table 3, in Fig. 3 denoted as OPs, i.e., optimised parameters**)**. For each parameter, a value range is defined. OPs are adjusted step-wise according to the set of values, defined in Table 3.

Beside optimised parameters (OP1, OP2 and OP3), the hydrogen demand ($Q_{H2\_OUT\_DEM}$), expressed in [kg/day], is also varied according to the following predefined values, see Table 4:

The simulation run is performed for each combination of values for the optimisation parameters and hydrogen demand, which gives in total 2688 combinations and the corresponding simulation runs. By varying more parameters, the number of combinations increases progressively, which leads to increased computational burden and possibly also an unpractically long total simulation time.

The other parameters that are not the subject of the optimisation are set to fixed, predefined values and are listed in Table 5 and denoted as "fixed parameters" in Fig. 3.

The HSCE results of each simulation run are:

- Time profiles of all process variables (mass-flow rates, energy flows, financial flows);
- Cumulative values of various output variables calculated during each simulation run on the basis of the input process variables. Several different values are calculated during each simulation run: the amount of hydrogen produced (m_{H2_PROD}), the hydrogen-production costs (PC_{H2}), the utilisation rate of the HS (c) and the income from hydrogen production ($Income_{H2}$).

Variables 1–3 represent the optimisation parameters (current values of the respective simulation run). Variables 7–10 represent the results of

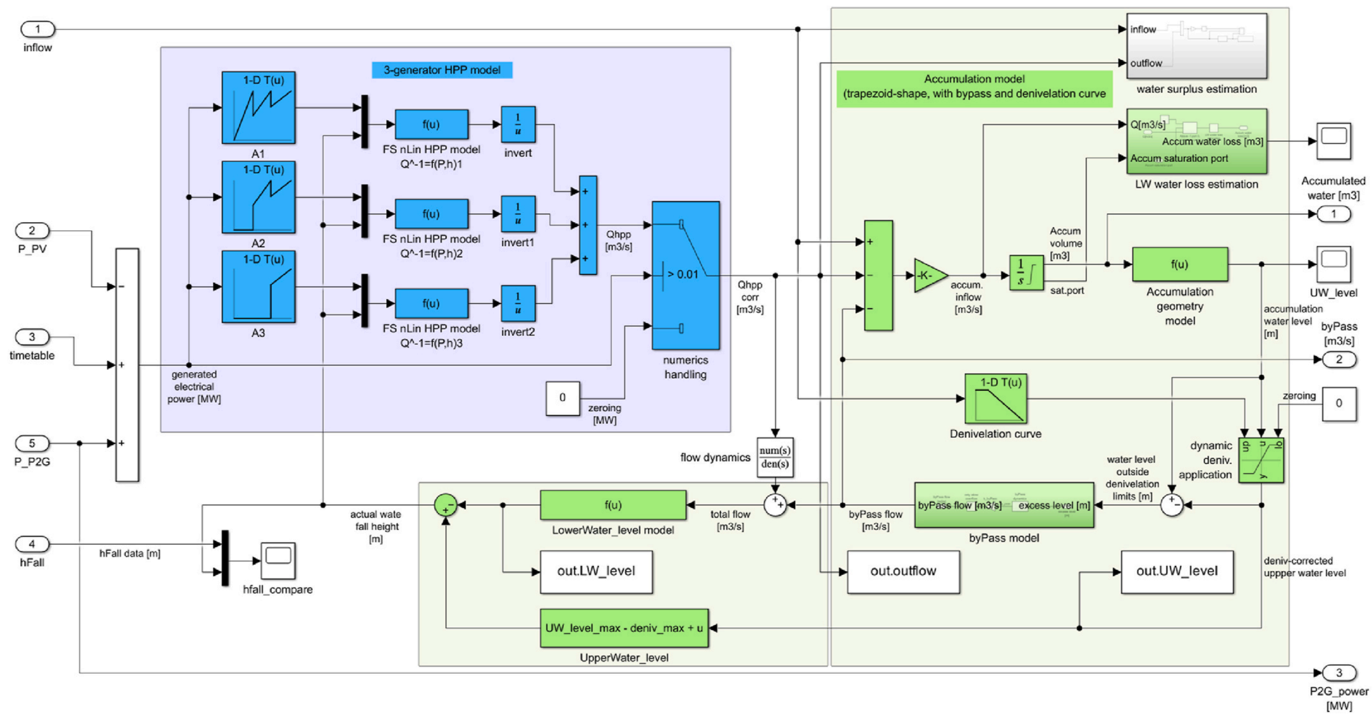

Fig. 10. Physical HPP model implemented in MATLAB/Simulink, with blue parts representing power-generation part and the green blocks the water accumulation part. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Control system look-up table (f_L as a function of SoC_W and p_{H2}).

	$SoC_W \leq 10$ %	10 % $<$ SoC_W ≤ 25 %	25 % $<$ $SoC_W \leq 65$ %	65 % $<$ $SoC_W <$ 85 %	$SoC_W \geq 85$ %
$p_{H2} \leq 50$ % · p_{H2_MAX}	0	0.2	0.5	0.8	1
50 % · p_{H2_MAX} $<$ $p_{H2} < 95$ % · p_{H2_MAX}	0	0.2	0.5	0.8	1
$p_{H2} \geq 95$ % · p_{H2_MAX}	0	0	0	0	0

Table 3
Parameters that are the subject of optimisation.

Parameter	Description	Unit	Set of values
OP1: P_{EL_SYS}	Nominal power of the HS	MW	[0.25 0.50 0.75 1.0 1.25 1.5]
OP2: P_{PV_INST}	Nominal power of the photovoltaic field	MW	[0 1 2 3 4 5 6]
OP3: V_{STOR}	Volume of the hydrogen storage tank	m^3	[10 20 30 40 50 60 70 80]

Table 4
Hydrogen demand.

Parameter	Description	Unit	Set of values
$Q_{H2\_OUT\_DEM}$	Assumed hydrogen consumption	kg/day	[80,160,240 320 400 480 560 640]

the various criteria functions of the respective simulation run. Variables 11–14 represent the financial parameters of the hydrogen and photovoltaic equipment. Parameters 4 and 5 provide information about the assumed hydrogen.

Table 5
Variables in the simulation result table (referred to as *simRes*).

N°	Parameter	Description	Unit
1	P_{PV_INST}	Nominal power of the photovoltaic field	MW
2	P_{EL_SYS}	Nominal power of the HS	MW
3	V_{STOR}	Volume of the hydrogen storage tank	m^3
4	$Q_{H2\_OUT\_DEM}$	Assumed hydrogen consumption per day	kg/d
5	SP_{H2}	Selling price of hydrogen	€/kg
6	*time*	Duration of the simulation in days	d
7	m_{H2_PROD}	Annual hydrogen production	kg/y
8	PC_{H2}	Hydrogen maximum production flow	€/kg
9	*c*	Utilisation rate of HS	–
10	$Income_{H2}$	Maximum hydrogen storage capacity	€/y
11	$CapEx_{PV}$	CapEx of the PV filed	€
12	$CapEx_{EL\_SYS}$	CapEx of the electrolyser system	€
12	$CapEx_{H2\_STOR}$	CapEx of hydrogen storage	€
14	*CapEx*	Total HS CapEx	€

8. Results and discussion

Fig. 11 illustrates the usability of the developed application (named HSCE) in presenting various techno-economic parameters across different system configurations. The application is designed to offer a high degree of flexibility, enabling users to explore the effects of four independently adjustable parameters. Given the complexity of visualising four-dimensional data, the interface allows users to manipulate one parameter via a slider, while simultaneously observing the behaviour of the remaining three.

To demonstrate the benefit of the developed HSCE, simulations of hydrogen and electrical power cogeneration in the case-study HPP were performed and the results were observed. The simulations help to determine the optimal parameters for the HS according to the case-study HPP's operating parameters. In the simulations, the following assumptions and limitations were considered:

- The operation of the HPP must fulfil the prescribed timetable of the supply of electrical power to the grid;

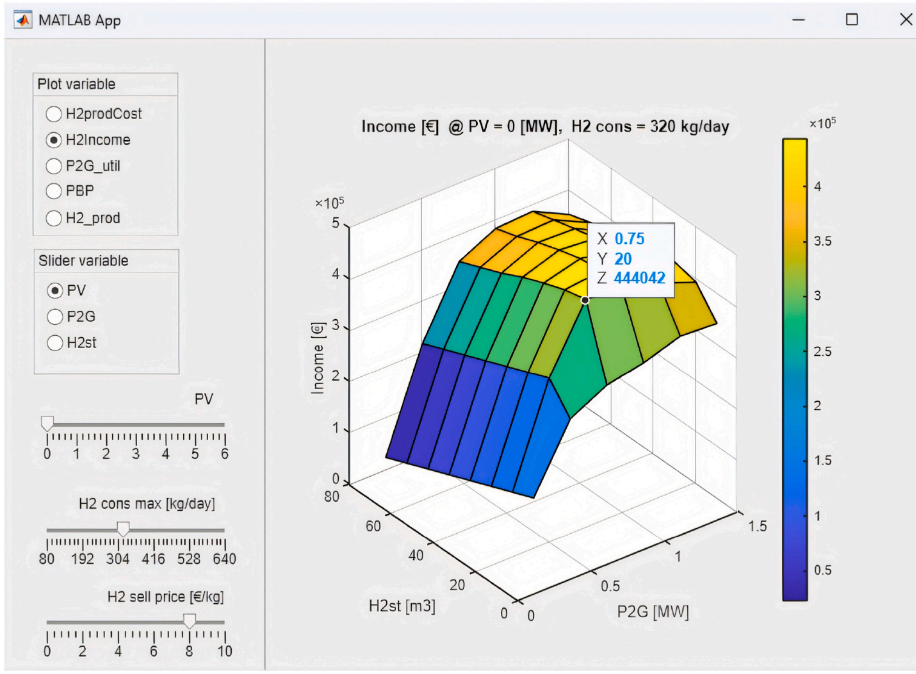

Fig. 11. Developed HSCE tool implemented in MATLAB App Designer.

- Only the surplus hydro energy and the electrical energy generated by the PV field can be used for the production of hydrogen;
- The required hydrogen production is moderate and limited to 320 kg/day;
- The price of surplus electrical power generated from surplus hydropower, which cannot be accepted by the grid, is considered zero;
- The price of electrical power generated that could be delivered to the grid, but is utilised for hydrogen production, is considered to be 38 €/MWh;
- The costs of electrical energy generated by the PV is taken into account by considering the CapEx and OpEx of the PV field.

As the HSCE is intended for use on a computer display, its interactive functionality cannot be fully represented in a static document. Therefore, the following results are illustrated using conventional static figures, which offer high visual quality but do not include the interactive controls available in the original application.

The case-study HPP operates continuously during a year and there are significant deviations in the water inflow or prescribed timetable, so we considered the sizing of the HS in January (with limited surplus of hydropower) and November (with ample surplus of hydropower) as interesting months to highlight differences in HS operation. In both experimental cases, two subcases were simulated: one without the PV field and the other with 6-MW nominal PV field. For both, the primary objective was to maximise income from hydrogen production ($Income_{H2}$). Additional input parameters included a hydrogen consumption demand ($Q_{H2\_OUT\_DEM}$) of up to 320 kg/day and a hydrogen selling price (SP_{H2}) of 8 €/kg.

Fig. 12 shows that the maximum monthly income in January, when ($P_{PV\_INST} = 0$ MW), can be obtained with a 0.75-MW HS and a 20 m^3 storage tank. The resulting income can reach up to 16,269 €/month. It is important to note, that in some system configurations, the income may even be negative.

The chosen HS configuration results in the amount of total hydrogen production in January (without the additional electrical energy from the photovoltaic field, i.e., ($P_{PV\_INST} = 0$ MW) of 4631 kg/month (see Fig. 13). This hydrogen production is only at the expense of the surplus of the water reserve in the accumulation and does not affect regular

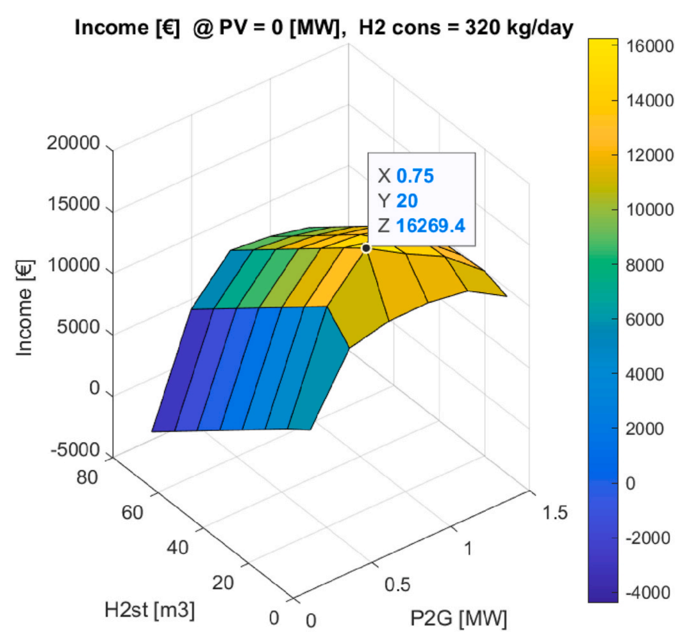

Fig. 12. Proposed system configuration for maximum income from hydrogen production in January.

electrical energy production due to the timetable.

Furthermore, the developed HSCE can be used as an estimator for the utilisation rate of the chosen HS configuration (see Fig. 14).

In this case, the 0.75-MW electrolyser utilisation rate (c) is around 45 %. The operation of the electrolyser can be seen in Fig. 15.

With inclusion of the PV field into additional source of electricity, the resulting income from hydrogen production was evaluated (see Fig. 16). It follows that the HS with a 0.75-MW electrolyser and 20 m^3 hydrogen storage cannot be profitable in any case, because the relatively small HS cannot produce enough hydrogen to cover the investment in a large PV field. The income for the proposed system setup is negative. In this system setup, losses of at least −3342 €/month are being generated. In

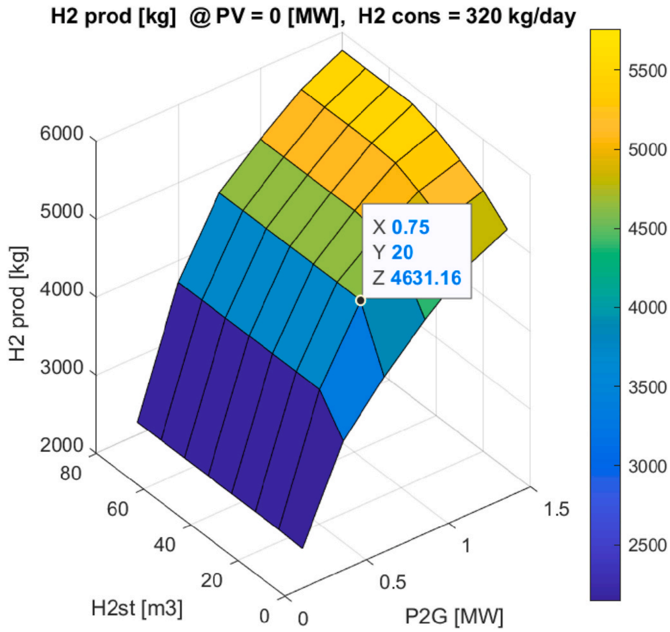

Fig. 13. Quantity of hydrogen produced in January.

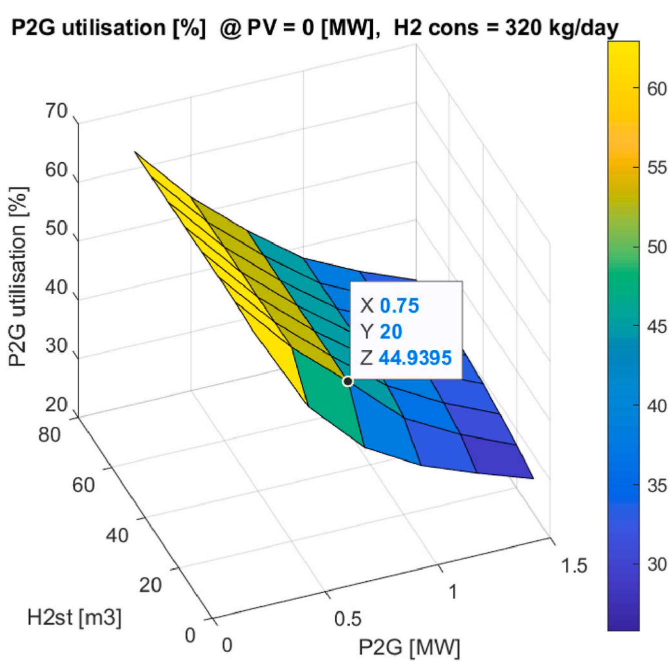

Fig. 14. Hydrogen-system utilisation rate in January.

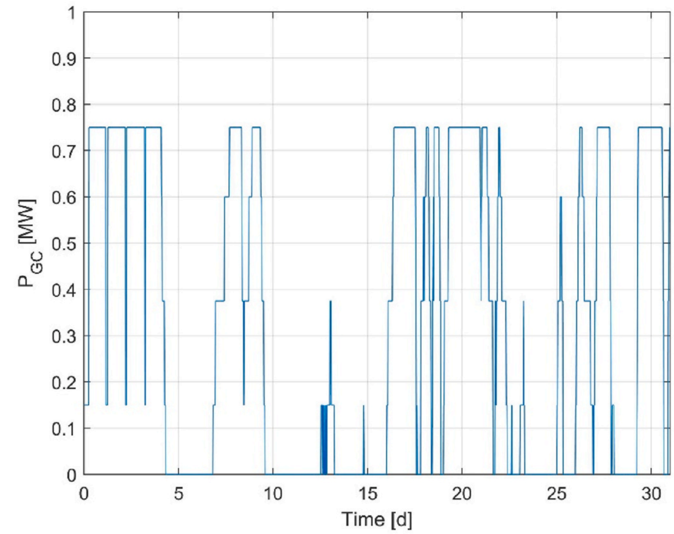

Fig. 15. HS's electrolyser operation in January.

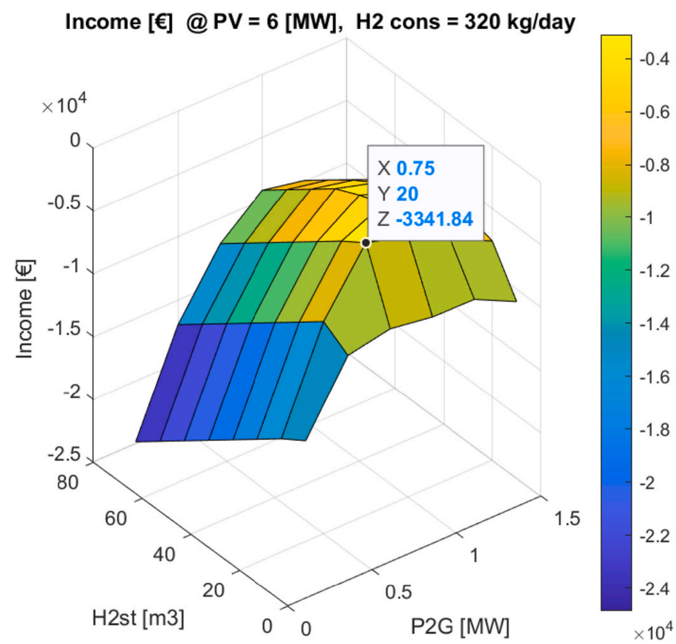

Fig. 16. Income in January after the inclusion of 6-MW PV field.

nearly all HS configurations, the income is negative due to the costs of PV field installation.

The same evaluation procedure for the HS was followed as in January; however, the month of November has been selected due to substantial surplus of hydro energy resulting from increased water inflow into the HPP during a prolonged period of rainfall. Fig. 17 shows the simulation results. As seen from Fig. 17, the maximum income from hydrogen production in November without the use of a PV field can be obtained with a 0.75-MW HS and a 20 m^3 storage tank for the assumed periodic consumption of hydrogen up to 320 kg/day and a hydrogen selling price of 8 €/kg. The resulting income can be as high as 52,652 €/month. In this case, the income is positive in all HS configurations.

The chosen hydrogen-system configuration results in a total hydrogen production in January at 9095 kg/month (see Fig. 18). This hydrogen production is only at the expense of the surplus of the water reserve in the accumulation, without the use of PV field capacities and does not affect regular electrical energy production due to the timetable.

Furthermore, the utilisation rate for the chosen HS configuration is in November around 92 % (see Fig. 19).

The operation of the electrolyser for November can be seen in Fig. 20.

The income from hydrogen production with the chosen HS configuration and included PV field capacities is seen in Fig. 21. The HS with a 0.75-MW electrolyser and 20 m^3 hydrogen storage is only profitable in certain cases, because the relatively small HS cannot produce enough hydrogen to cover the investment in a large PV field.

From the above sections we can see that there are significant differences when operating in particular months, which can affect the justification of the investment in the HS. To get a clear and complete picture of the HS's operation and proper selection of its components, a simulation must be performed for the period of one year.

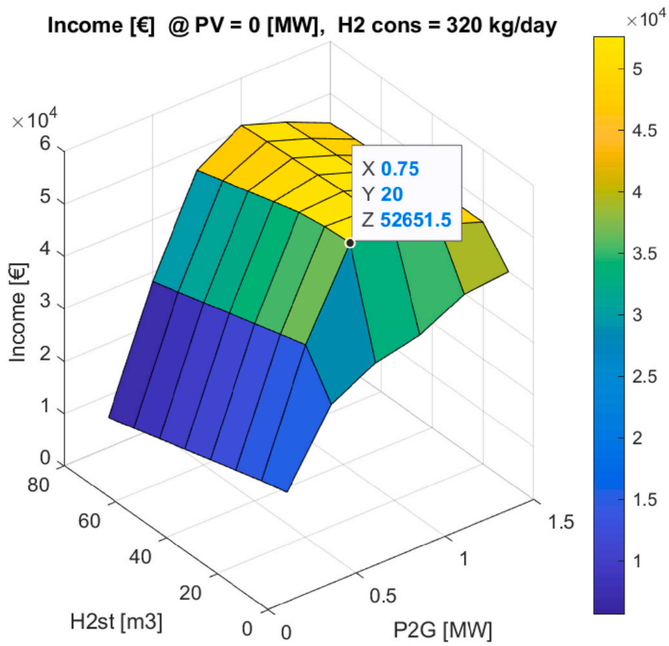

Fig. 17. Proposed HS configuration for maximum income from hydrogen production in November.

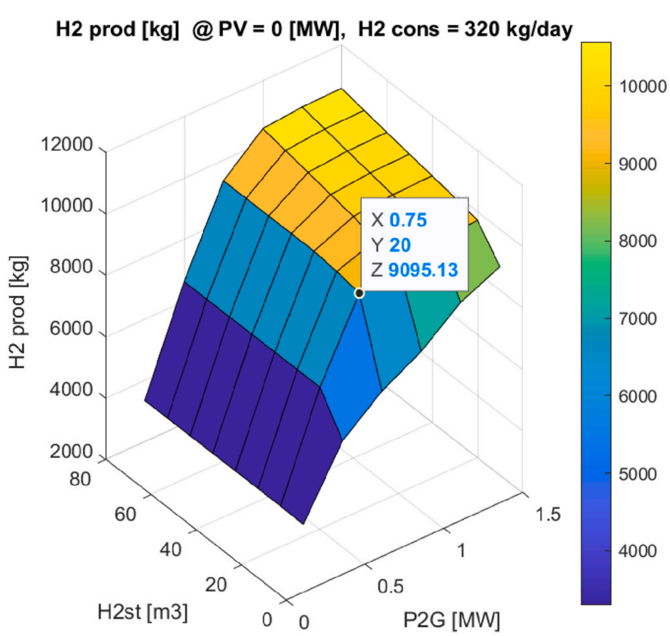

Fig. 18. Monthly hydrogen quantity produced in November.

Fig. 22 show the annual simulation results. The maximum annual income, when ($P_{PV\_INST} = 0$ MW), can be as in previous cases obtained with a 0.75-MW HS and a 20 m^3 storage tank for the assumed periodic consumption of hydrogen up to 320 kg/day and a hydrogen selling price of 8 €/kg. The resulting income can be as high as 444,042 €/year.

Please note, when the equipment is inappropriately dimensioned, the $Income_{H2}$ may take on a negative value. This happens in cases where the equipment is oversized, too expensive (high CapEx) or underutilised (low hydrogen-system utilisation rate (c)). In this case the investment costs exceed the income from the sale of hydrogen. The chosen HS configuration results in a total annual hydrogen production (without the additional electrical energy from the photovoltaic field, i.e., ($P_{PV\_INST} = 0$ MW)) of 86,087 kg/year (see Fig. 23).

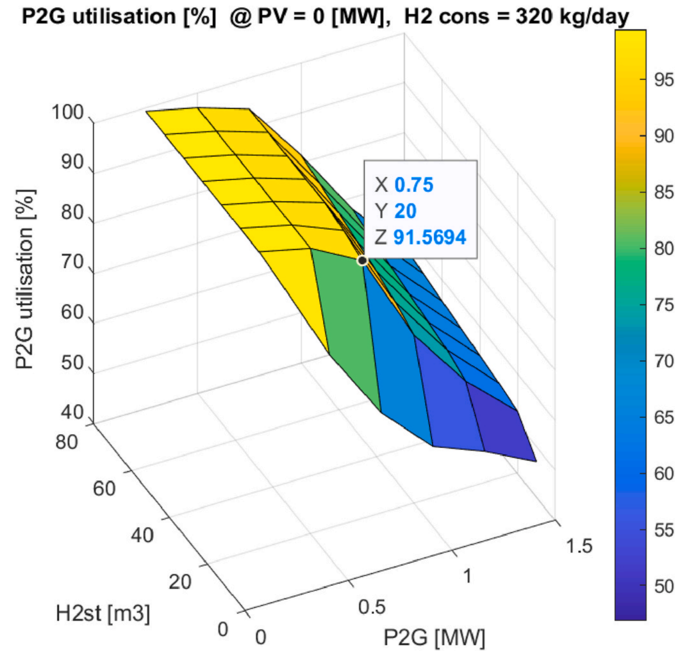

Fig. 19. Hydrogen-system utilisation rate in November.

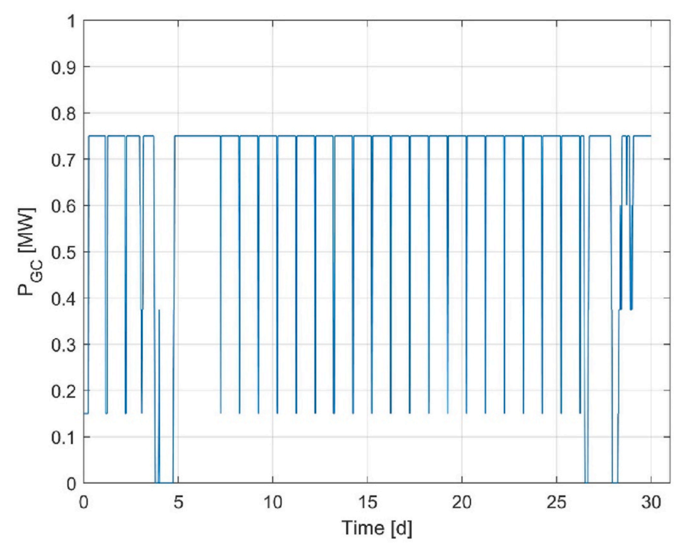

Fig. 20. HS's electrolyser operation in November.

Furthermore, the HSCE calculates the maximal utilisation rate of the chosen HS configuration at around 71 % (see Fig. 24).

The annual operation of the selected HS's electrolyser can be seen in Fig. 25.

By inclusion of the PV field's capacities, the income from hydrogen production is lower (see Fig. 26). The HS with a 0.75-MW electrolyser and 20 m^3 hydrogen storage cannot be profitable in all configurations (a too small electrolyser cannot produce enough hydrogen to cover the investment in a larger PV field).

By further increasing the PV field to 6 MW, it is possible to increase the utilisation rate of the electrolyser up to approximately 92 % (see Fig. 27).

The annual operation of the electrolyser can be seen in Fig. 28.

The results emphasise the usefulness of the developed HSCE tool, implemented in MATLAB App Designer, in evaluating the techno-economic performance of HSs under different operating conditions. The flexibility of the application in interactively adjusting four

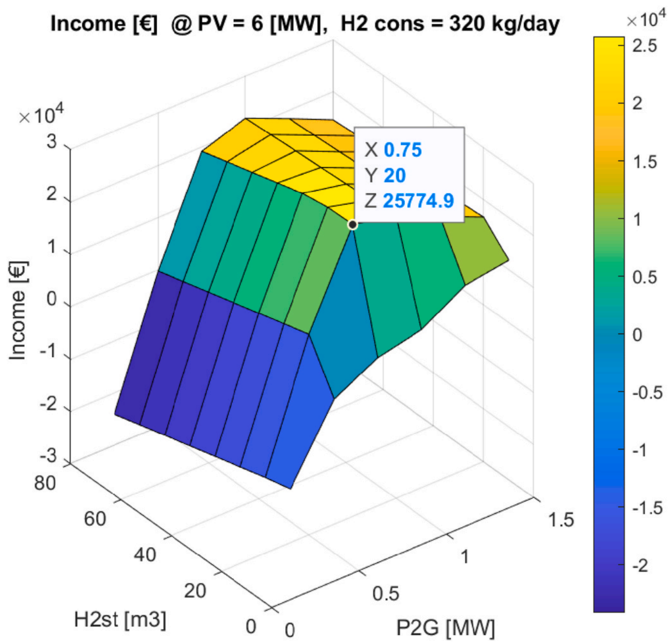

Fig. 21. Income in November after the inclusion of 6-MW PV field.

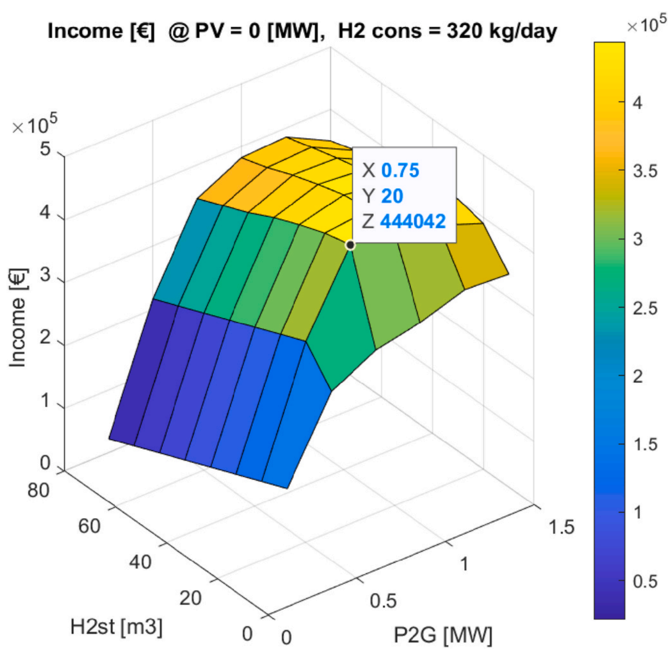

Fig. 22. Proposed HS configuration for maximum annual income from hydrogen production.

parameters provides nuanced insights into hydrogen and electricity cogeneration in a HPP. The simulations performed for January and November, reflecting a low and high surplus of hydropower respectively, show significant differences in hydrogen production and economic viability. In particular, a 0.75-MW electrolyser with a 20 m^3 storage tank delivers optimal results in scenarios without PV field, generating a monthly income of up to 52,652 € in November. However, the inclusion of a 6-MW PV field generally makes the system economically unviable, as the hydrogen production is not sufficient in relation to the investment costs. Annual analyses confirm this trend and show that profitability depends on appropriate dimensioning and utilisation of the system, with the HSCE proving to be a guide for such optimisation. The

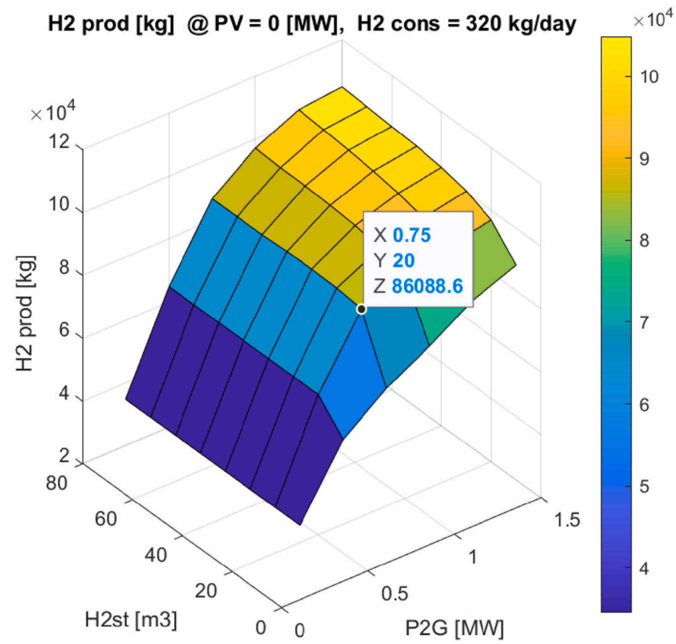

Fig. 23. Annual hydrogen quantity produced.

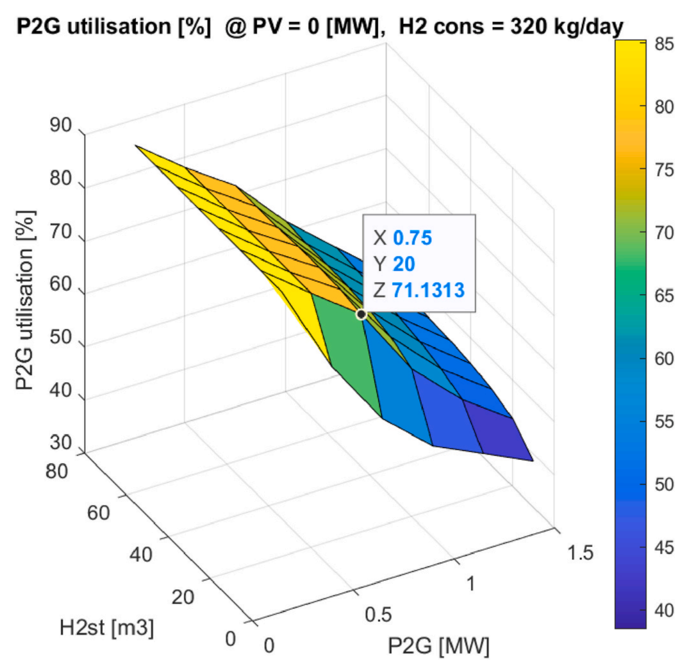

Fig. 24. Annual HS's utilisation rate.

study shows the importance of customised configurations and comprehensive temporal simulations to ensure sustainable investment decisions in hydrogen infrastructure. These findings not only validate the HSCE tool as a decision-support instrument but also highlight its relevance in the broader context of sustainable energy planning and policy, which the following conclusions further explore.

9. Conclusions

Hydrogen is a key energy vector for achieving the long-term green transition. While the majority of current production relies on steam reforming of natural gas, this method is incompatible with climate objectives. In contrast, green hydrogen, produced via water electrolysis

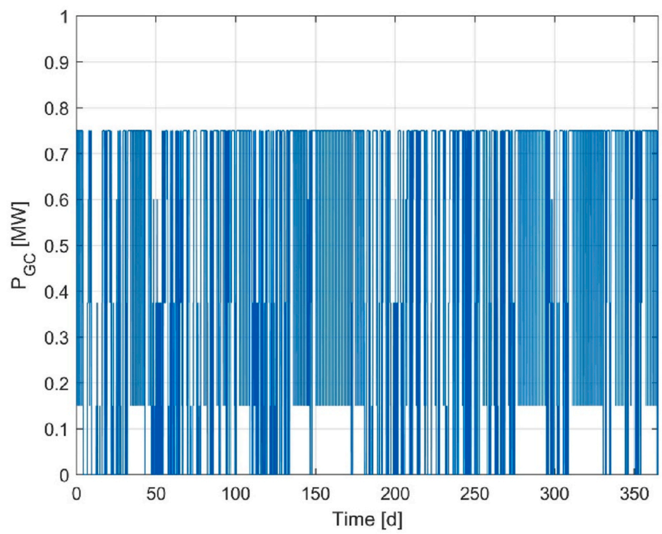

Fig. 25. Annual HS's operation.

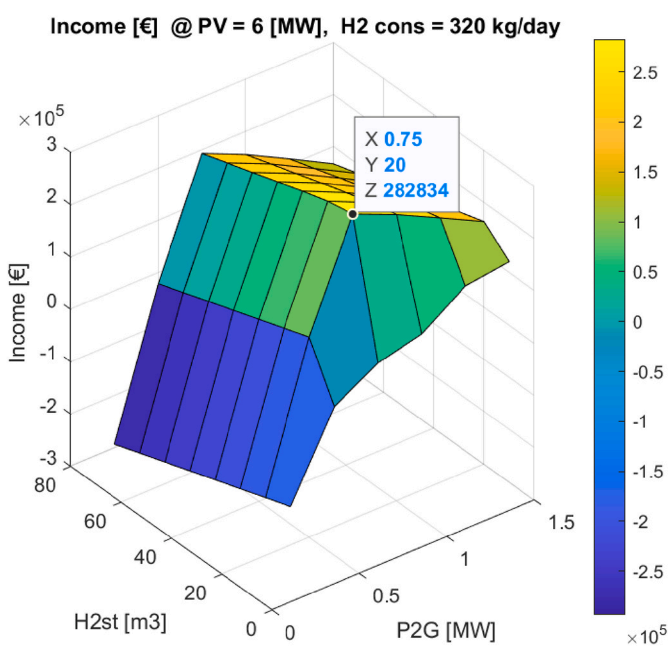

Fig. 26. Annual income after the inclusion of 6-MW PV field.

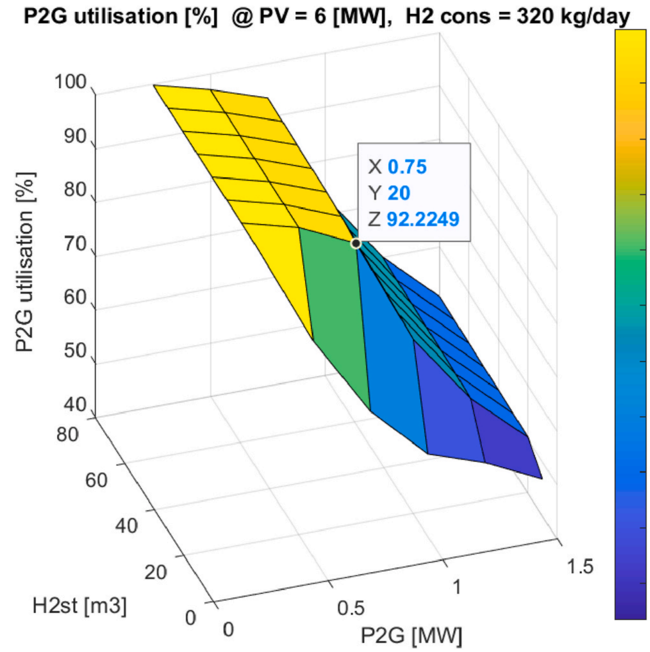

Fig. 27. Annual HS's utilisation rate using 0.75-MW electrolyser with the inclusion of 6-MW PV field.

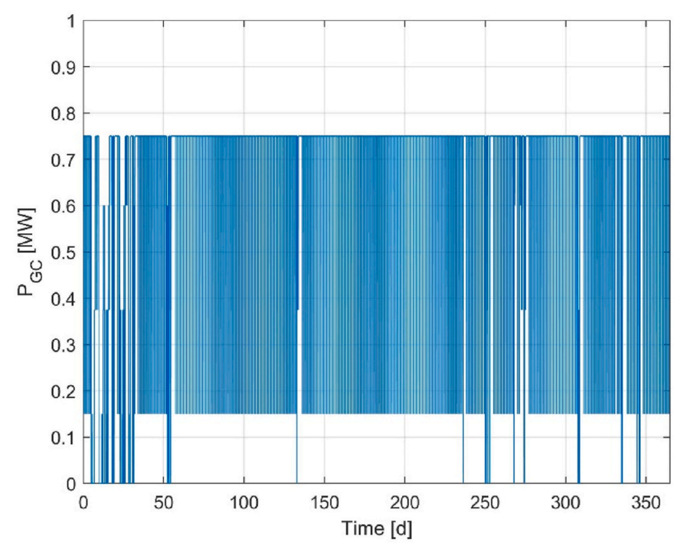

Fig. 28. Annual HS's operation after the inclusion of 6-MW PV field.

using renewable electricity, presents notable advantages, including reductions in CO_2 emissions, enhanced energy independence, and support for sustainable development. HPPs, as the most dependable source of renewable electricity, offer significant potential for the cogeneration of green hydrogen, although the integration of HS into HPP operations remains insufficiently explored. This study provides a technical and economic assessment of hydrogen production in conjunction with HPPs. It outlines a methodology for simulating HS operation using real-world data, estimating capital and operational costs, and evaluating financial feasibility. A comprehensive model of the integrated HS-HPP system was developed, examining the utilisation of surplus hydropower for hydrogen generation, with profitability assessed under varying market scenarios. To aid decision-making, a HSCE was introduced to facilitate optimal component sizing based on electricity surplus and projected hydrogen demand. The tool incorporates sensitivity analysis and a basic control algorithm to manage HS operation in real time. Findings from the case study indicate that, under favourable conditions, investment in HSs may already be economically viable, with anticipated reductions in component costs likely to further enhance profitability. Nonetheless, certain limitations of the HSCE remain. The accuracy of outcomes is restricted by the discretisation of the parameter space, and computational constraints limit the number of parameters that can be feasibly optimised. Moreover, alterations to non-optimised parameters necessitate a complete repetition of simulations, thereby reducing procedural flexibility. These challenges underscore the need for future developments in model precision, computational efficiency, and adaptability to improve its practical application in complex scenarios.

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CRediT authorship contribution statement

David Jure Jovan: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Writing – review & editing. **Boštjan Pregelj:** Methodology, Data curation. **Mihael Sekavčnik:** Validation, Supervision, Resources. **Gregor Dolanc:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Formal analysis.

Declaration of competing interest

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

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