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Research Paper

Design of hydrogen production systems powered by solar and wind energy: An insight into the optimal size ratios

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ABSTRACT

Green hydrogen is expected to play a crucial role in the future energy landscape, particularly in the pursuit of deep decarbonisation strategies within hard-to-abate sectors, such as the chemical and steel industries and heavy-duty transport. However, competitive production costs are vital to unlock the full potential of green hydrogen. In the case of green hydrogen produced via water electrolysis powered by fluctuating renewable energy sources, the design of the plant plays a pivotal role in achieving market-competitive production costs. The present work investigates the optimal design of power-to-hydrogen systems powered by renewable sources (solar and wind energy). A detailed model of a power-to-hydrogen system is developed: an energy simulation framework, coupled with an economic assessment, provides the hydrogen production cost as a function of the component sizes. By spanning a wide range of size ratios, namely the ratio between the size of the renewable generator and the size of the electrolyser, the cost-optimal design point (minimum hydrogen production cost) is identified. This investigation is carried out for three plant configurations: solar-only, wind-only and hybrid. The objective is to extend beyond the analysis of a specific case study and provide broadly applicable considerations for the optimal design of green hydrogen production systems. In particular, the rationale behind the cost-optimal size ratio is unveiled and discussed through energy (utilisation factors) and economic (hydrogen production cost) indicators. A sensitivity analysis on investment costs for the power-to-hydrogen technologies is also conducted to explore various technological learning paths from today to 2050. The optimal size ratio is found to be a trade-off between the utilisation factors of the electrolyser and the renewable generator, which exhibit opposite trends. Moreover, the costs of the power-to-hydrogen technologies are a key factor in determining the optimal size ratio: depending on these costs, the optimal solution tends to improve one of the two utilization factors at the expense of the other. Finally, the optimal size ratio is foreseen to decrease in the upcoming years, primarily due to the reduction in the investment cost of the electrolyser.

1. Introduction

Hydrogen is envisaged to play an important role in decarbonising those sectors where emissions are hard to abate and alternative solutions are either unavailable or difficult to implement [1]. The current production of hydrogen (mainly to supply refineries and the chemical industry) is almost entirely dominated by fossil sources (natural gas and coal), and low-emission hydrogen accounts for <1% of total production [2]. Therefore, green hydrogen share must increase significantly to support the global energy transition and meet the rising demand from both traditional and new markets (industry [3], aviation [4], shipping and heavy transport [5]). According to the International Renewable Energy Agency (IRENA) [6], hydrogen production in 2050 will increase 7–8 times compared to the current values: green hydrogen, mainly from water electrolysis fed by renewable energy sources (RES), will cover 62–100% of the hydrogen demand, while blue hydrogen will account for the remaining share. As reported by the International Energy Agency (IEA) [7], the global interest in green hydrogen is testified by the growing number of countries that are adopting hydrogen strategies and

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Nomenclature

Acronyms

BOP	Balance of plant
BT	Battery
CAPEX	Capital expenditure
CF	Capacity factor
EL	Electrolyser
LCOH	Levelised cost of hydrogen
LHV	Lower heating value
NPC	Net present cost
OPEX	Operating expenditure
PEM	Polymer electrolyte membrane
PtH	Power to hydrogen
PV	Photovoltaic
RES	Renewable energy sources
SOC	State-of-charge
SU	Surplus
USD	United States dollar
WT	Wind turbine

Symbols

A_{BT}	Battery autonomy, h
$C_{capex,i}$	Investment cost for the component *i*, €
C_{H_2}	LCOH of the PtH system, €/kg
$C_{opex,tot,i,n}$	Total operating cost for the component *i* during year *n*, €
C_{rate}	C-rate parameter of the battery, h^{-1}
C_{tot}	NPC of the PtH system, €
$CF_{PV,t}$	PV capacity factor in time step *t*, %
$C_{SU,n}$	Revenue for the sale of electricity to the grid during year *n*, €
$CF_{WT,t}$	WT capacity factor in time step *t*, %
c_{sell}	Sale price of electricity to the grid, €/kWh
dt	Duration of the time step, h
$E_{BT,t}$	Energy stored in BT in time step *t*, kWh
$E_{BT,max}$	Maximum energy in BT (based on SOC_{max}), kWh
$E_{BT,min}$	Minimum energy in BT (based on SOC_{min}), kWh
$E_{BT,rated}$	Battery rated energy, kWh
$M_{H_2,n}$	Annual hydrogen production during year *n*, kg
N	Project lifetime, yr
n	Year $n \in \{1,\ldots, N\}$ of the project lifetime, yr
$P_{BT,c,t}$	Battery charging power in time step *t*, kW
$P_{BT,d,t}$	Battery discharging power in time step *t*, kW
$P_{BT,max,c}$	Maximum battery charging power, kW
$P_{BT,max,d}$	Minimum battery discharging power, kW
$P_{EL,in,t}$	Electrolyser input power in time step *t*, kW
$P_{EL,min}$	Electrolyser minimum power, kW
$P_{EL,out,t}$	Electrolyser output power (hydrogen) in time step *t*, kW
$P_{EL,rated}$	Electrolyser rated power, kW
$P_{RES,t}$	Power from RES generators in time step *t*, kW
$P_{PV,rated}$	PV rated power, kW
$P_{PV,t}$	Power from PV in time step *t*, kW
$P_{SU,t}$	Surplus power in time step *t*, kW
$P_{WT,rated}$	WT rated power, kW
$P_{WT,t}$	Power from WT in time step *t*, kW
t	Time step $t \in \{1,\ldots, T\}$ of the energy simulation
T	Number of time steps in the time horizon of the energy simulation
U_{EL}	Utilisation factor of the electrolyser, %
U_{RES}	Utilisation factor of the RES generator, %
z	Discount rate
$\eta_{BT,c}$	Battery charging efficiency, %
$\eta_{BT,d}$	Battery discharging efficiency, %
$\eta_{EL,t}$	Electrolyser efficiency in time step *t*, %

targets for technology deployments. IEA also foresees that the electrolyser installed capacity will reach 134–240 GW by 2030.

Green hydrogen is currently 2–3 times more expensive to produce than grey hydrogen. However, the falling costs of renewable electricity and the improvements in electrolysis technology are rapidly enhancing the competitiveness of low-carbon hydrogen [8]. In this evolving context, optimal design of power-to-hydrogen (PtH) systems is also necessary to deliver green hydrogen at the lowest specific cost. Numerous works in the literature have addressed this challenge, as evidenced below.

1.1. Power-to-hydrogen systems

This section presents literature works focused on the design of power-to-hydrogen plants and the existing research gap associated. A common method is to carry out techno-economic assessments of hydrogen production systems with predefined component sizes. For example, Mazzeo et al. [9] investigated the performance of fixed-size hydrogen production plants powered by photovoltaic (PV), wind turbine (WT) and hybrid configurations, installed in twenty-eight different locations worldwide. Additionally, a simplified approach can be found that considers the same size for the renewable generator and the electrolyser. This assumption was applied in the work by Janssen et al. [10], who explored country-specific costs for renewable hydrogen production, focusing on the use of photovoltaic and wind energy in various European countries. They approximated the RES and the electrolyser design by using average annual capacity factor (CF) values and assuming a size ratio of 1. The resulting levelised cost of hydrogen (LCOH) values were in the range 2.1–15 €/kg in 2020 and 1.6–8.4 €/kg in 2050.

The available literature also includes various modelling frameworks aimed at providing the cost-optimal design point (minimum LCOH) for renewable-based hydrogen production systems. In this context, some studies have developed techno-economic optimisation tools to directly determine the cost-optimal sizes of the involved technologies for a specific case study. Trapani *et al.* [11] employed a metaheuristic-based optimisation approach to explore the cost-effectiveness of on-site green hydrogen production in a semiconductor production plant. A multi-objective optimisation methodology based on a genetic algorithm variant was used by Park *et al.* [12], who conducted a techno-economic analysis of green hydrogen production systems powered by solar energy. Marocco *et al.* [13] formulated a mixed-integer linear programming (MILP) tool capable of providing both optimal component sizes and optimal scheduling for PV-based grid-connected hydrogen production systems.

The works mentioned above do not deal with the behaviour of the LCOH as a function of the size of the PtH components (RES generator and electrolyser). This aspect has been investigated in other literature studies, such as the one conducted by Khan *et al.* [14], who assessed the cost of hydrogen by varying the capacities of PV and WT across different production sites in Australia. Their aim was to identify optimal hubs (in terms of size and geographical location) for the production of green hydrogen at competitive cost (lower than 2 USD/kg). Uchman *et al.* [15] explored the impact of the electrolyser configuration in a PtH system powered by solar and wind energy. The authors proposed a technical-only optimisation of the electrolyser rated power and achieved an optimal electrolyser size of about 5 MW for a hybrid solar-wind plant of 10 MW.

Among the works that addressed the impact of component sizes on the LCOH, some studies also presented the results in terms of size ratios. The techno-economic viability of PV-based hydrogen production plants was investigated by Gallardo *et al.* [16], who varied the inverter and electrolyser capacity and found a minimum LCOH of 5.9 USD/kg (Atacama, Chile). Grube *et al.* [17] examined PV-based hydrogen production plants with variable component sizes, finding an optimal ratio between PV and electrolyser capacities of 1.4–2. A simplified analysis of size ratios for a PV-only case study can also be found in the McKinsey's Electric Power & Natural Gas Practice 2022 report [18]. Wind-based hydrogen production plants were analysed by Scolaro and Kittner [19]. They investigated offshore wind farms in Germany and observed that the lowest cost occurred when the electrolyser size was approximately 87% of the wind farm capacity. Wind-based layouts were also examined in the work of Sorrenti *et al.* [20], who studied hydrogen production for a Danish industrial park. Their findings indicated that the most effective configuration involved a grid-connected setup with a wind farm three times the size of the electrolyser. Both solar- and wind-based electrolyser systems were explored by Hofrichter *et al.* [21] and Zhang *et al.* [22], but none of them included the hybrid PV-WT configuration. Similarly, the IRENA 2022 report on the costs and potential of green hydrogen [23] considered PV-only and WT-only configurations, extending the analysis to several countries across the world.

Most of the literature presented so far has provided the reader with the design conditions (in terms of component sizes) that lead to the minimum hydrogen production cost, i.e., the cost-optimal design point. While some of these studies have also included the influence of component sizes (sometimes expressed as size ratios) on the optimal LCOH, none offered insights into the motivations behind the derived optimal design point. These are essential for understanding how the optimal size ratios, and the associated LCOH, vary in response to a change in boundary conditions. The literature would also benefit from applying such an approach to a set of different plant configurations including PV, WT and hybrid systems, which are typically not addressed together within the same study.

1.2. Novelty and aim of the study

The present work aims to investigate the optimal combination of sizes for the RES generators and the electrolyser, aiming to achieve maximum hydrogen production at the minimal cost. The main contributions to the existing literature are:

- In contrast to previous works, this study unveils and thoroughly discusses the rationale behind the optimal size ratios between the PtH components. This is performed by introducing a set of energy indicators (electrolyser and RES utilisation factors) and economic indicators (hydrogen production cost, including the breakdown between RES and electrolyser contributions). They enable an understanding of how the cost-optimal design point changes as the boundary conditions vary.
- The proposed approach is not tied to any specific case study (no constraints on the hydrogen demand) to further expand the applicability of the results.
- The analysis also encompasses different system configurations according to the RES typology: PV-only, WT-only and hybrid (i.e. both PV and WT).
- As the investment costs for electrolysers and RES technologies are expected to decrease in the coming decades [24], the optimal size ratios – and associated LCOH values – are investigated over different time horizons (from today to 2050).

The final goal of this research is to provide guidelines for industry, policy makers and stakeholders on how to optimally design green hydrogen production systems. Since hydrogen has gained significant interest in recent years and special incentives are being allocated at national and European level, the provision of guidelines for designing power-to-hydrogen plants becomes essential. Equally important is understanding the reasons behind the cost-optimal design point through a simplified and replicable methodology.

The analysis is applied to Italy where hydrogen is being supported by national policies as part of the Italian Recovery Plan 2022 [25]. Country-aggregated hourly profiles of PV and WT capacity factors are employed to perform the energy simulation of the PtH system. The results are also strengthened by using a real efficiency curve of a proton exchange membrane (PEM) electrolyser to accurately simulate its part-load performance.

The paper is structured as follows: Section 2 describes the model of the RES-based PtH system and presents the main techno-economic data for the analysis. The results are then shown and discussed in Section 3, and finally conclusions are reported in Section 4.

2. Materials and methods

This section details the methodology employed in the study, encompassing the description of plant configurations (Section 2.1), the energy simulation approach (Section 2.2), the technical, energy and economic indicators utilised to present the results (Section 2.3), and a summary of all input data for the model (Section 2.4).

2.1. Power-to-hydrogen configurations

Based on the RES generator technology, four different PtH configurations have been investigated (see also Fig. 1).

a. **PV-only**: PV is the only energy source for hydrogen production.
b. **WT-only**: WT is the only energy source for hydrogen production.
c. **Hybrid**: PV and WT are the energy sources for hydrogen production.
d. **Hybrid with battery**. PV and WT are the energy sources for hydrogen production. Battery storage (BT) is also available to maximise the use of local RES.

As shown in Fig. 1, it should be noted that this study concentrates on the supply side of the hydrogen value chain (i.e. on the hydrogen production stage). Specifically, the focus is on PtH plants powered by on-site RES with the aim of maximising the hydrogen production at the least cost without constraints related to hydrogen supply.

In all these configurations, a PEM electrolyser (EL) was considered to produce green hydrogen. Indeed, PEM electrolysers are currently the most suitable option for integration with variable RES [6], due to their faster dynamic response, higher current density, extended modulation range and enhanced stability over time compared to other technological options already on the market [26].

The methodological approach employed in this study is depicted in Fig. 2. The analysis starts from a fixed-size energy simulation integrated with an economic assessment (white box in Fig. 2). This model, detailed in Section 2.2, allows the calculation of a set of energy and economic indicators (discussed in Section 2.3). Afterwards, an external routine (yellow box) is introduced to perform a sensitivity analysis spanning a wide range of size ratios – i.e. the ratio between the size of the renewable generator and the size of the electrolyser – as well as battery autonomy values. Specifically, the sensitivity analysis covers size ratios from 0.5 to 8 and battery autonomy values from 0 to 6 h, ensuring the identification of the point with the minimum LCOH.

Through this analysis, the trends of the energy and economic indicators as a function of the design ratios are achieved, and the cost-optimal design point (minimum LCOH) is determined. This framework is developed for three plant configurations: PV-only, WT-only and hybrid systems.

2.2. Energy simulation

The sizes of the components of the PtH system (PV, WT, electrolyser

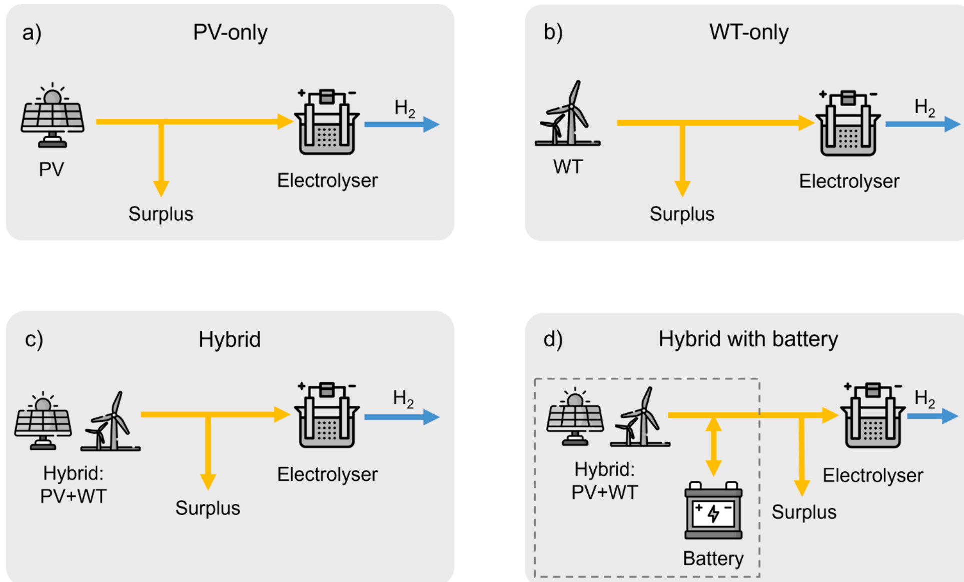

Fig. 1. Layout of the four PtH configurations: (a) PV-only, (b) WT-only, (c) Hybrid, and (d) Hybrid with battery.

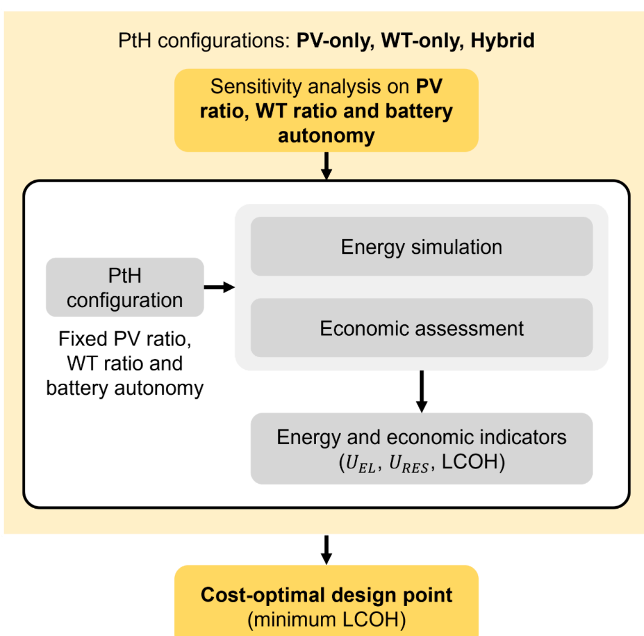

Fig. 2. Schematic of the methodological approach for the optimal design of PtH systems.

and battery) were set as input data for the techno-economic assessment.

Two design indicators, defined by Eqs. (1) and (2), were introduced to express the ratio between the rated capacities of the RES generators ($P_{PV,rated}$ and $P_{WT,rated}$, in kW) and the rated capacity of the electrolyser ($P_{EL,rated}$, in kW) [13].

$$PVratio = \frac{P_{PV,rated}}{P_{EL,rated}} \tag{1}$$

$$WTratio = \frac{P_{WT,rated}}{P_{EL,rated}} \tag{2}$$

When referring generally to the PV ratio or the WT ratio, the term RES ratio is used from now on.

The battery rated energy ($E_{BT,rated}$, in kWh) was defined in terms of hours of autonomy (A_{BT}, in h) with respect to the electrolyser rated power and was evaluated according to Eq. (3). Specifically, the A_{BT} parameter indicates how long the battery storage is able to cover the energy demand of the electrolyser under rated conditions [13].

$$A_{BT} = \frac{E_{BT,rated}}{P_{EL,rated}} \tag{3}$$

For each PtH configuration, the operation of the system was modelled using a rule-based control logic. Fig. 3 shows the logical block diagram for the simulation of the RES-electrolyser-battery system. A description of all the symbols used can be found in the Nomenclature Section.

A time horizon of 1 year was considered for the energy simulation. The time resolution of each time step (t) of the simulation is given by dt, and T is the number of time steps that are present in the time horizon. In this analysis an hourly time step resolution was considered, i.e. dt is equal to 1 h and T is equal to 8760 (i.e. number of hours in a year).

For each time step of the simulation ($t \in \{1,\ldots,T\}$), the energy system wass regulated based on the difference between the power produced by the RES generators ($P_{RES,t}$) and the rated power of the electrolyser ($P_{EL,rated}$). The $P_{RES,t}$ term was computed based on the hourly capacity factors of PV ($CF_{PV,t}$) and/or WT ($CF_{WT,t}$), as shown by the following expression:

$$P_{RES,t} = P_{PV,rated} \cdot CF_{PV,t} + P_{WT,rated} \cdot CF_{WT,t} \tag{4}$$

The capacity factor of PV and WT was defined as the ratio of the electrical energy produced by the renewable generator over a given time step t to the theoretical maximum electrical energy production over that period. For each time step t, it can be defined as follows (with i = PV, WT) [27]:

$$CF_{i,t} = \frac{P_{i,t} \cdot dt}{P_{i,rated} \cdot dt} \tag{5}$$

where $P_{i,t}$ (in kW) is the power produced by the i-th renewable generator (i.e. PV or WT), and dt (in h) is the duration of the time step.

If the RES power is higher than $P_{EL,rated}$, the electrolyser is supplied with a power equal to $P_{EL,rated}$. Excess power is then stored in the battery storage, depending on the state-of-charge (SOC) and the C-rate parameter of the battery, to be used later by the electrolyser for hydrogen production. Finally, surplus power, if any, is not exploited by the PtH system.

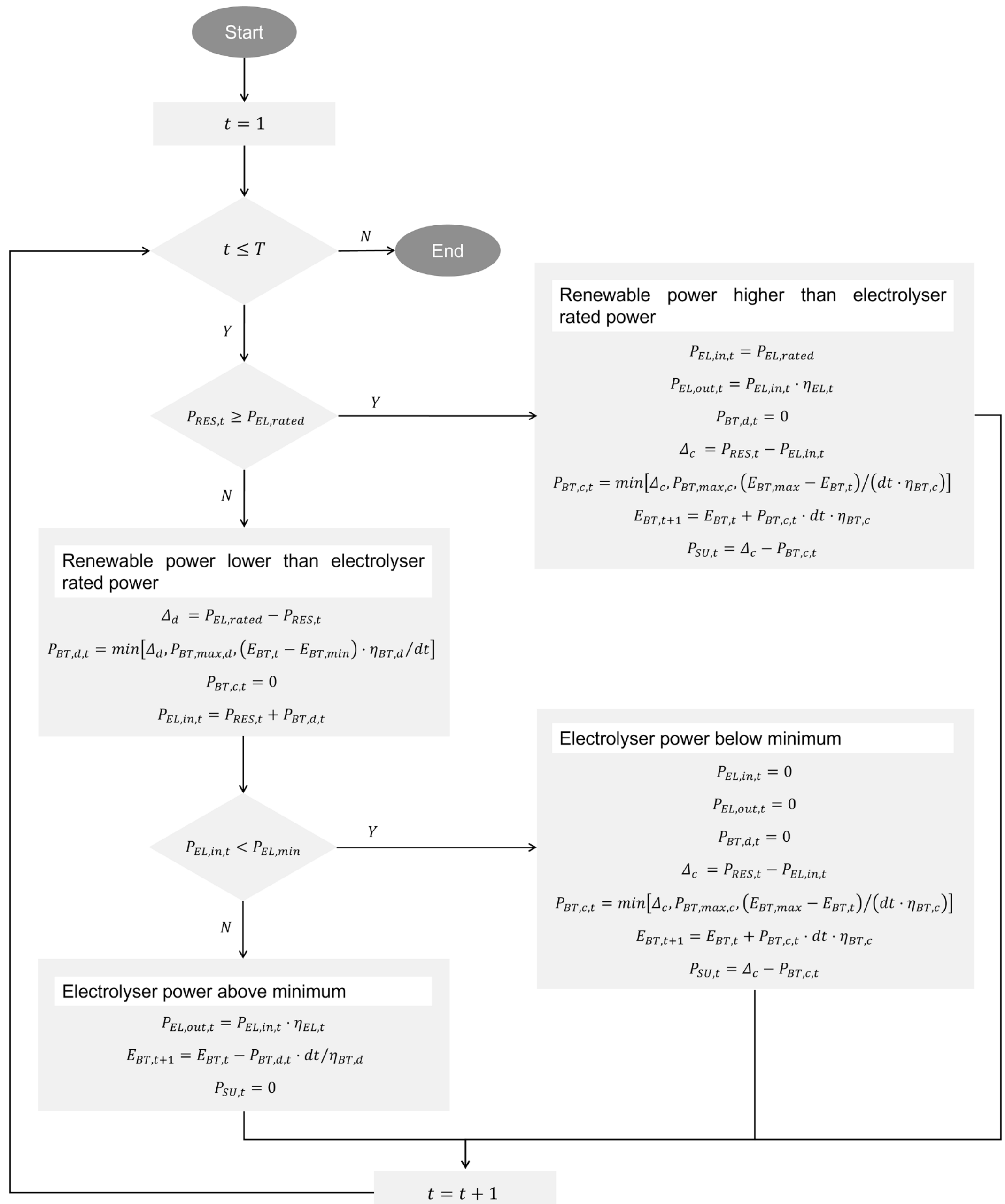

Fig. 3. Logical block diagram for the energy simulation of the RES-electrolyser-battery system. Refer to the Nomenclature Section for a description of the symbols used.

If the power from the RES generators is lower than $P_{EL,rated}$, the battery is discharged (based on its SOC and C-rate parameter) to maximise the electrolyser operating point. Only in cases where the resulting input power of the electrolyser ($P_{EL,in,t}$) is lower than its minimum power ($P_{EL,min}$), the electrolyser is kept off and the renewable power is stored in the battery until its maximum SOC is reached. Therefore, when the electrolyser is in operation, it must always operate at a power higher than $P_{EL,min}$. Indeed, in order to ensure efficient and safe operation of the electrolyser, it is necessary to establish a minimum power threshold. Too low partial loads would lead to safety issues (related to hydrogen cross-diffusion [28]) and to a sharp drop in system efficiency (due to the power consumption of the auxiliary components).

In the Appendix, all equations used to model the battery storage are described in detail.

For each of the 4 PtH configurations (see Fig. 1), the control logic described in Fig. 3 was applied, setting to zero the sizes of the components that are not involved in the energy system.

2.3. Energy and economic indicators

Based on the energy simulation, two energy performance indicators were evaluated, namely the utilisation factor of the electrolyser (EL utilisation, U_{EL}) and the utilisation factor of the RES generators (RES utilisation, U_{RES}) [13]. The U_{EL} indicator measures the actual energy utilisation of the electrolyser compared to the maximum amount of energy it could utilise within a given time horizon without any interruption, as expressed below:

$$U_{EL} = \frac{\sum_{t=1}^{T}\left(P_{EL,in,t}\cdot dt\right)}{\sum_{t=1}^{T}\left(P_{EL,rated}\cdot dt\right)} \quad (6)$$

where $P_{EL,in,t}$ (in kW) is the input power to the electrolyser in time step t, $P_{EL,rated}$ (in kW) is the rated power of the electrolyser, dt (in h) is the duration of the time step and T is the number of time steps in the selected time horizon.

The other indicator (U_{RES}) expresses how much of the energy available from the renewable plant is exploited for hydrogen production by the electrolyser. It was evaluated as follows:

$$U_{RES} = \frac{\sum_{t=1}^{T} (P_{EL,in,t} \cdot dt)}{\sum_{t=1}^{T} (P_{RES,t} \cdot dt)} \tag{7}$$

where $P_{RES,t}$ (in kW) is the RES power production in time step t, which was computed according to Eq. (4).

An economic analysis over the project lifetime (number of years N of operation) was also developed to estimate the LCOH of the PtH system. The LCOH is the economic indicator on which the optimal system design is based. First, the net present cost (NPC) of the RES-electrolyser-battery system (C_{tot}, in €) was defined according to the following expression (with i = PV, WT, BT, EL) [11]:

$$C_{tot} = \sum_{i} \left[C_{capex,i} + \sum_{n=1}^{N} \frac{C_{opex,tot,i,n}}{(1+z)^n} \right] \tag{8}$$

where $C_{capex,i}$ is the investment cost of component i, $C_{opex,tot,i,n}$ is the total operating cost of component i during year n, and z is the discount rate. For each component, the $C_{opex,tot,i,n}$ term includes the operating, replacement, and salvage contributions. The replacement cost was determined based on the lifetime of the component. Surplus electricity ($P_{SU,t}$ in Fig. 3) was not accounted for as revenue in the economic assessment in order to optimally design the energy system based on a pure PtH business case (i.e. maximise the RES utilisation to produce hydrogen at the least cost).

The LCOH (C_{H_2}, in €/kg) was then assessed as follows [11]:

$$C_{H_2} = \frac{C_{tot}}{\sum_{n=1}^{N} \left[M_{H_2,n} \cdot (1+z)^{-n} \right]} \tag{9}$$

where $M_{H_2,n}$ (in kg) is the annual hydrogen production.

2.4. Techno-economic input data

Country-aggregated profiles of the capacity factors of PV and WT (onshore), with hourly resolution, were used to estimate the renewable generation potential in Italy. The data – shown in Fig. 4 – were taken from [29] and refer to the year 2016, which was outlined as the most-typical reference weather year for Italy [30]. The resulting annual average CFs are 15.5% for PV and 19.5% for WT (onshore).

Table 1 shows all the technical and economic parameters used in the analysis, for each component of the PtH system and with related literature sources. The efficiency curve of the electrolyser, depicted in Fig. 5, refers to a MW-size PEM electrolyser and was derived from [31]. The

Table 1
Techno-economic assumptions for the current scenario.

Parameter	Value	Ref.
Photovoltaic		
CAPEX	650 €/kW	[33]
OPEX (annual)	2% (% of CAPEX)	[34]
Lifetime	Project lifetime	
Wind turbine (onshore)		
CAPEX	1120 €/kW	[33]
OPEX (annual)	3% (% of CAPEX)	
Lifetime	Project lifetime	
Battery storage		
Charging efficiency	95%	[35]
Discharging efficiency	95%	[35]
Minimum SOC	20%	[35]
Maximum SOC	100%	[35]
C-rate	1C	
CAPEX (module + BOP)	306 €/kWh	[36]
Replacement cost (module)	50% (% of CAPEX)	[35]
OPEX (annual)	2% (% of CAPEX)	[35]
Lifetime of the BT module	10 yr	[35]
Lifetime of the BOP	Project lifetime	
Electrolyser		
Minimum power	5% (% of rated power)	[37]
Maximum power	100% (% of rated power)	
Efficiency	Efficiency curve	[31]
CAPEX (stack + BOP)	1188 €/kW	[24]
Replacement cost (stack)	30% (% of CAPEX)	[38]
OPEX (annual)	3% (% of CAPEX)	
Lifetime of the stack	65,000 h	[32]
Lifetime of the BOP	Project lifetime	
Other assumptions		
Project lifetime	20 yr	
Discount rate	4%	

CAPEX: capital expenditure, OPEX: operating expenditure.

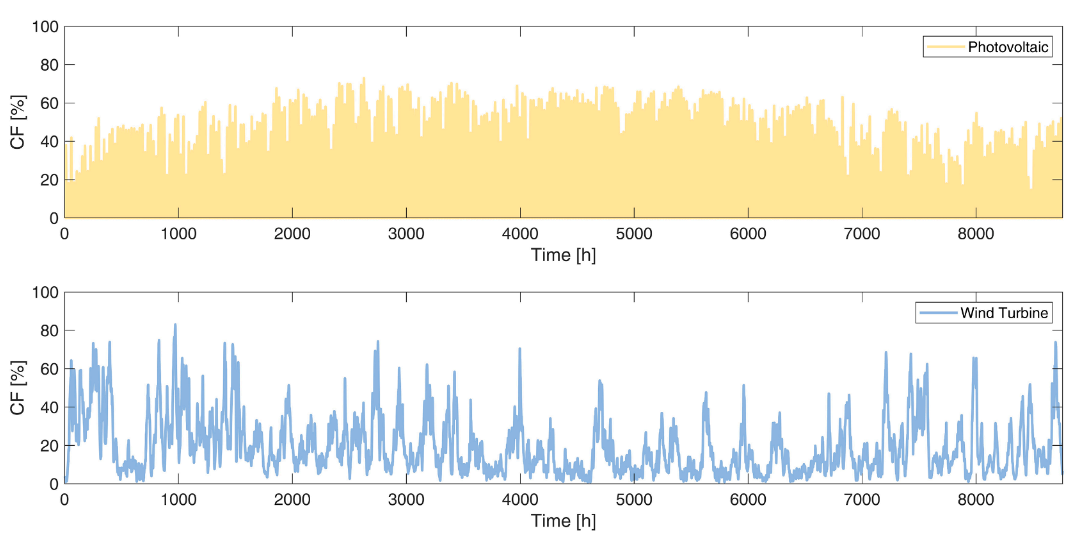

Fig. 4. Hourly time series of PV and WT (onshore) capacity factors over the reference year (2016) in Italy.

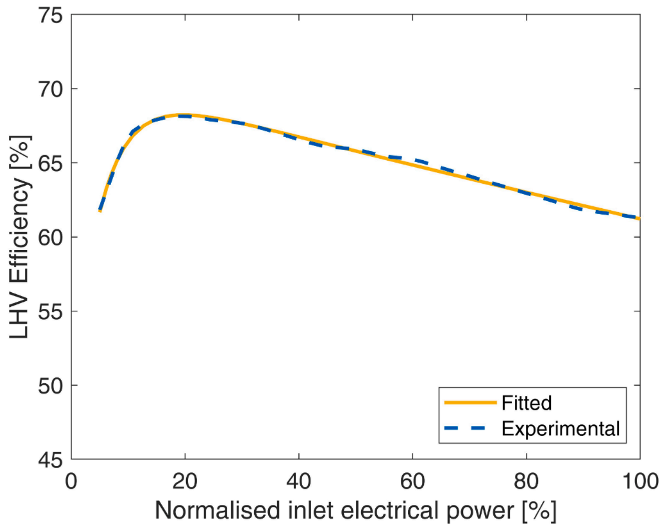

Fig. 5. Efficiency (based on LHV) of the PEM electrolyser system as a function of the normalised inlet electrical power.

lower heating value (LHV) efficiency at rated power is 61.2%, while the peak efficiency is 68.2% (at about 20% of rated power). The current investment cost for the electrolyser system – including the stack and balance of plant (BoP) components – was set to 1188 €/kW [3], which is deemed representative of the current electrolyser market [32]. The economic analysis also takes into account the lifetime of the electrolyser stacks and the associated replacement costs, which are determined based of the actual operating hours of the electrolyser.

The analysis was first performed based on the reference values given in Table 1. Then, a sensitivity analysis on the investment costs of the PtH components was carried out to analyse the impact of capital expenditures on the optimal size ratios (and associated LCOH values). Specifically, the CAPEX was varied in the following range: 300–700 €/kW (for the PV), 800–1200 €/kW (for the wind turbine), 200–1300 €/kW (for the electrolyser). As shown in Table 2, specific cost projections were also pointed out for the short-term (2030) and long-term (2050) scenarios.

3. Results and discussion

The results are first presented considering the current investment costs (Section 3.1). The costs of the PtH technologies are then varied to assess how they may influence the optimal design of the PtH system; future cost scenarios are also highlighted (Section 3.2). The sizing variables are expressed in normalised form (in terms of size ratios) to avoid being tied to a specific case study and to provide a general overview of the optimal design of RES-based hydrogen production systems.

3.1. Current cost scenario

In the current cost scenario, the results initially focus on the PV-only and WT-only configurations (Section 3.1.1) to highlight the reasons behind the optimal design points. Afterward, the findings on the hybrid PV-WT configuration are presented (Section 3.1.2).

Table 2
CAPEX for PV, WT, BT and EL in current and future (2030, 2050) cost scenarios.

CAPEX	Current	2030	2050
Photovoltaic [33]	650 €/kW	450 €/kW	350 €/kW
Wind turbine [33]	1120 €/kW	1040 €/kW	960 €/kW
Battery storage [36]	306 €/kWh	175 €/kWh	131 €/kWh
Electrolyser [24]	1188 €/kW	701 €/kW	314 €/kW

3.1.1. Single-generator configurations

The main sizing results of the PV-only and WT-only PtH systems are shown in Fig. 6 and Fig. 7, respectively. The energy (U_{RES} and U_{EL}) and economic (LCOH) indicators are reported as a function of the PV and WT ratios, which are varied between 0.5 and 8. The results are based on the techno-economic data reported in Table 1 (current cost scenario). The cost-optimal design point, corresponding to the minimum LCOH value, is also highlighted in red in the figures.

The minimum LCOH for the PV-only configuration (Fig. 6) is about 5.11 €/kg and is achieved with a PV ratio of 2.2 (i.e. the PV rated power is 2.2 times greater than the electrolyser rated power). At the optimal design point, the PtH system is able to exploit 90.8% of the PV energy for hydrogen production (U_{RES}), and the utilisation factor of the electrolyser (U_{EL}) is 31.3%. When the PV ratio is below 2.2, the U_{EL} indicator decreases sharply, leading to a significant increase in the electrolyser cost share (as shown by the green area in Fig. 6b). In this region, the decrease in the utilisation factor of the electrolyser is the predominant effect on the LCOH, even if the renewable generator is better exploited, as testified by the U_{RES} indicator that is close to 100%. On the contrary, when the PV ratio is above 2.2., the increase in U_{EL} is not sufficient to compensate for the abrupt reduction in U_{RES}. This decrease in the RES utilisation leads to a considerable rise in the PV cost share (as displayed by the yellow area in Fig. 6b), with a consequent increase in the overall LCOH.

The optimal solution for the WT-only configuration is shown in Fig. 7. It can be seen that a minimum LCOH of 5.76 €/kg is achieved for a WT ratio of 2.8 (i.e. the WT rated power is 2.8 times greater than the electrolyser rated power). In this configuration, the WT utilisation amounts to 90.8% and the electrolyser utilisation is 48.6%. The U_{RES} and U_{EL} indicators (Fig. 7a) again show opposite trends as discussed for the PV-only case study.

By comparing the PV-only and WT-only solutions, it is worth noting that the WT-only plant can achieve an optimal U_{EL} value of 48.6%, which is higher than that of the PV-only plant (31.3%), even though the optimal RES utilisation is similar in the two configurations (around 90.8%). The difference in the optimal U_{EL} value (despite similar RES utilisations) can be attributed to multiple factors: the higher capacity factor of WT compared to PV (the average annual CF value is 19.5% for WT and 15.5% for PV), the more stable generation profile of WT compared to PV, and the higher optimal value of the WT ratio (2.8) compared to the PV ratio (2.2). A higher U_{EL} value has a beneficial effect on the electrolyser cost share, as can be seen from the green area in Fig. 7b (WT-only), which is smaller than the green area in Fig. 6b (PV-only). However, the cost share of the wind turbine (blue area in Fig. 7b) is greater than the cost share of PV (yellow area in Fig. 6b). This is because the higher capacity factor of WT compared to PV is not sufficient to compensate for the higher specific cost of the WT technology (1120 €/kW for WT and 650 €/kW for PV). This leads to a higher LCOH for the WT-only configuration due to the predominant contribution of the WT cost (even if the cost share of the electrolyser is lower in the WT-only case compared to the PV-only case).

Some works from the literature pointed out the minimum LCOH with respect to the component sizes ([18,17] for PV-only configurations, [22,21] for both PV-only and WT-only configurations). In the current cost scenario, the minimum LCOH is found for the following size ratios: 1.4–2 [17] and 2.2 [23] for PV-only scenarios, and close to 3 for WT-only scenarios [22]. These outcomes support the findings of the present study. Higher variations in the optimal size ratios can be found in extreme conditions of RES availability, as shown in [21]. However, none of the above-mentioned works provides information on the rationale behind the optimal design point, which is clearly related – as demonstrated above – to a set of energy indicators. These indicators also allow the comprehension of the optimal size ratio under variable boundary conditions (e.g. changes in the investment cost of the technologies as discussed in Section 3.2).

It should be noted that – in this analysis – the cost-optimal assess-

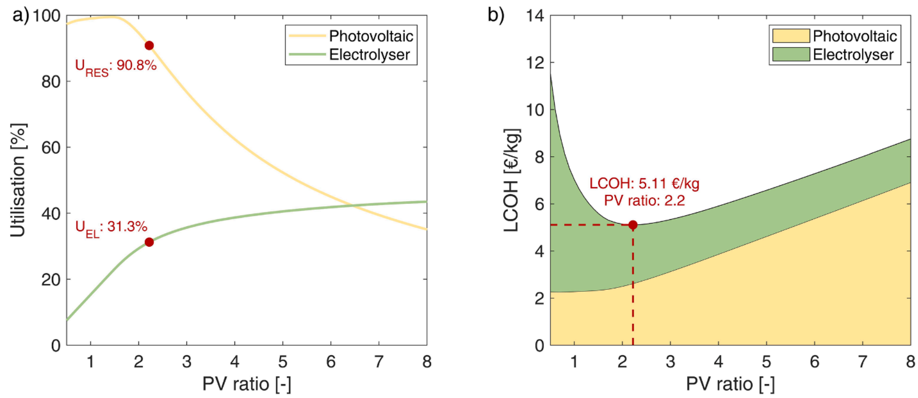

Fig. 6. PV-only configuration: (a) RES and EL utilisation as a function of the PV ratio, (b) LCOH as a function of the PV ratio. Results refer to the current cost scenario.

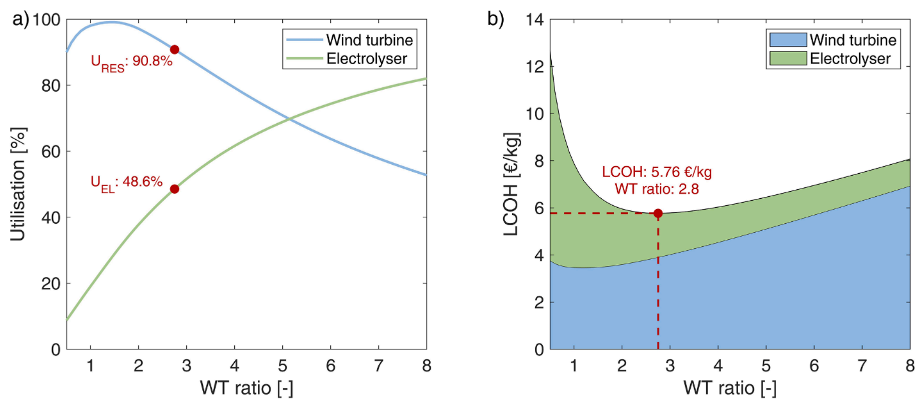

Fig. 7. WT-only configuration: (a) RES and EL utilisation as a function of the WT ratio, (b) LCOH as a function of the WT ratio. Results refer to the current cost scenario.

ment was computed with a sale price for the surplus electricity equal to zero. By increasing the electricity sale price, the optimal RES ratio would progressively increase due to the shift towards an electricity-driven business case, where the main purpose becomes to sell renewable electricity (the impact of the electricity sale price on the PtH optimal design is deepened in the Appendix B). Therefore, since the focus of this work is a PtH business case, the electricity sale price was set to zero for the assessment of the optimal size ratios. Once the optimal design point is determined, an electricity sale price higher than zero could be considered in the LCOH evaluation to represent the case of remuneration for the surplus of electricity fed into the grid. However, the improvement (reduction) in LCOH would be limited since most of the electricity is used for hydrogen production (as shown by the high optimal U_{RES} values in Figs. 6 and 7).

3.1.2. Hybrid configurations

Hybrid configurations were also investigated to assess the influence of combining PV and WT generators. The results are shown in Fig. 8, where both the PV ratio and the WT ratio are varied from 0.5 to 8. The LCOH, U_{EL} and U_{RES} values of the cost-optimal hybrid configuration are highlighted in white in Fig. 8. The optimal hybrid solution is characterised by a lower LCOH value (5.04 €/kg) compared to the PV-only (5.11 €/kg) and WT-only (5.76 €/kg) configurations, and the optimal size ratio is 1.6 for both PV and WT. Almost identical PV and WT capacities were also computed by Fasihi and Breyer [39] for hybrid PtH systems under cost-optimal conditions. Similarly, Janssen *et al.* [10] assumed the same size for the PV and WT generators in the design of RES-based hydrogen production systems.

The positive effect of combining PV and WT is also underlined by the improvement in the energy performance indicators. In the optimal hybrid configuration, the RES utilisation is over 92% (Fig. 8c) and the electrolyser utilisation is almost 52% (Fig. 8b). In contrast, the U_{EL} indicator was 31.1% and 47.9% for the optimal PV-only and WT-only configurations, respectively. Therefore, if optimally designed, a hybrid system can result in lower hydrogen production costs with improved utilisation of the electrolyser and the RES generators.

Different PtH configurations were also analysed by varying the value of the battery autonomy (A_{BT}) from 0 (reference case) to 6 h. For each value of A_{BT}, the results of the cost-optimal sizing process are listed in Table 3. Specifically, in order to determine the design point with the minimum LCOH value, the optimal design was computed by performing a sensitivity analysis on the PV and WT ratios, as previously described.

The first row of Table 3 corresponds to the optimal hybrid configuration without battery, which is highlighted in white in Fig. 8. By increasing the battery autonomy, the optimal WT ratio remains almost constant (1.6–1.7 in all configurations), while the optimal PV ratio increases from 1.6 to 3.1. The electrolyser utilisation (U_{EL}) also increases from 51.6% to 73.1% when the battery autonomy is increased from 0 to 6 h. Despite the positive effect of the battery on the electrolyser utilisation, the high battery CAPEX always leads to an increase in the LCOH value. Indeed, the cost of hydrogen production increases from 5.04 to 6.34 €/kg (+26%) when moving from 0 to 6 h of battery autonomy.

Therefore, the introduction of a battery storage – to optimise the RES utilisation and maximise hydrogen production – turns out to be not convenient from an economic point of view (in terms of LCOH), even if it contributes to improving the U_{EL} indicator.

3.2. Future cost scenarios

Electrolysers and renewable energy generators are expected to

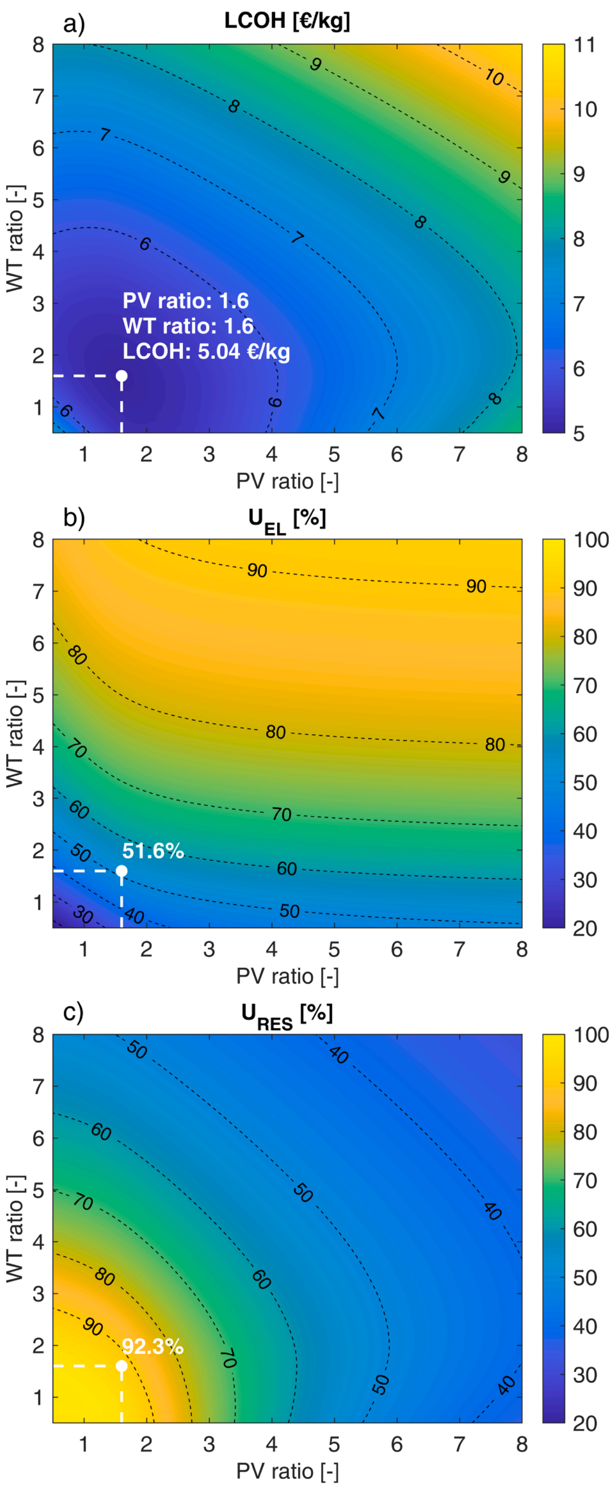

Fig. 8. Hybrid configuration: (a) LCOH, (b) EL utilisation and (c) RES utilisation as a function of the PV ratio and WT ratio. Results refer to the current cost scenario.

experience profound cost reductions in the coming decades, through technological learning, mass production and economies of scale. Therefore, the influence of the investment costs of the technologies on the optimal design of the PtH system was investigated. Furthermore, current, short- and long-term scenarios were defined using the data listed in Table 2.

Table 3
Cost-optimal configuration with battery storage. The battery autonomy is varied from 0 to 6 h. Results refer to the current cost scenario.

A_{BT} [h]	PV ratio [-]	WT ratio [-]	U_{EL} [%]	U_{RES} [%]	LCOH [€/kg]
0	1.6	1.6	51.6	92.3	5.04
1	1.9	1.7	56.5	92.3	5.29
2	2.1	1.7	60.5	91.9	5.52
3	2.4	1.7	64.4	91.4	5.74
4	2.6	1.7	67.2	91.2	5.95
5	2.8	1.7	70.1	90.9	6.15
6	3.1	1.7	73.1	90.4	6.34

3.2.1. Single-generator configurations

Figs. 9 and 10 show the results for the PV-only and WT-only configurations. For each combination of RES CAPEX and electrolyser CAPEX, results refer to the optimal solution, which was derived by performing a sensitivity analysis on the PV and WT ratios to identify the design point with the minimum LCOH value.

As shown in Fig. 9a, a reduction in the PV investment cost (at fixed electrolyser CAPEX) leads to a shift towards higher optimal PV ratios. Lower PV investment costs indeed make it cost-effective to install larger PV systems in order to increase the electrolyser utilisation (U_{EL}), with a consequent reduction in the electrolyser cost share. On the contrary, if the electrolyser investment cost is reduced (at fixed PV CAPEX), the optimal PV ratio decreases, as it becomes economically convenient to operate the electrolyser at a lower U_{EL} while enhancing the RES utilisation (U_{RES}). When moving from the current to the 2030 and 2050 scenarios, both PV and electrolyser costs are expected to decline, resulting in a combined effect of the two trends discussed above. The global effect is a reduction in the optimal PV ratio: the reduction in the electrolyser CAPEX is therefore predominant compared to the reduction in the PV CAPEX. Fig. 9a shows that the optimal PV ratio decreases from 2.2 in the current scenario to 2.1 in 2030 and 1.9 in 2050. The cost of hydrogen production also decreases from the current to the future scenarios (see Fig. 9b). Specifically, the LCOH, which is equal to 5.11 €/kg at current technology costs, drops to 3.28 €/kg in 2030 and 2.04 €/kg in 2050.

Concerning the WT-only configuration, the optimal values of WT ratio and LCOH are presented in Fig. 10 as a function of the CAPEX of WT and electrolyser. Similar to the PV-only configuration, the optimal WT ratio decreases when moving from the current to the future scenarios, as a result of the combined effect of reducing the WT CAPEX (higher WT ratio) and the electrolyser CAPEX (lower WT ratio). Because the expected reduction in the WT CAPEX is fairly limited, the reduction in the electrolyser CAPEX has a more prevailing effect on the variation of the RES ratio compared to the PV-only case: in fact, moving from the current to the 2050 scenario, the WT ratio decreases from 2.8 to 1.9 in the WT-only configuration (Fig. 10a), while the PV ratio only decreases from 2.2 to 1.9 in the PV-only configuration (Fig. 9a). The LCOH reduction compared to the PV-only case is also minor: from 5.76 €/kg in the current scenario to 4.69 €/kg in 2030 and 3.71 €/kg in 2050.

3.2.2. Hybrid configurations

The impact of the investment costs of the PtH technologies was also assessed for the hybrid configuration (i.e. both PV and WT). However, due to the higher number of variables (i.e. CAPEX of PV, WT and electrolyser), only the results of the optimal hybrid solution for the current, 2030 and 2050 scenarios are presented in Fig. 11. The cost of the PV technology is expected to decrease by 46% between the current and 2050 scenarios, while the reduction in the WT cost for the same period is only 14%. This discrepancy in projected cost reduction favours PV over WT in the optimal design of future hybrid configurations. Fig. 11a shows that the optimal WT ratio decreases from 1.6 in the current scenario to zero in the 2030 and 2050 scenarios. In contrast, the optimal PV ratio first rises from 1.6 (current scenario) to 2.1 (2030) to compensate for the absence of WT, and then falls to 1.9 (2050) in line with the trend

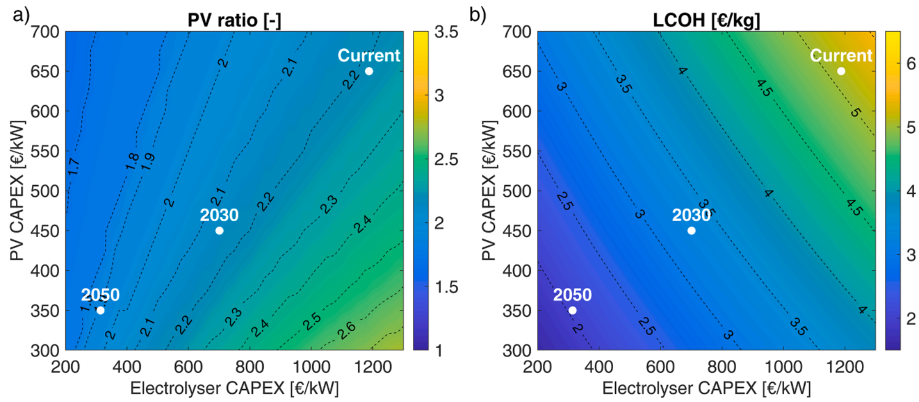

Fig. 9. PV-only configuration: (a) PV ratio and (b) LCOH as a function of the CAPEX of electrolyser and PV. Current, 2030 and 2050 cost scenarios are based on the data shown in Table 2.

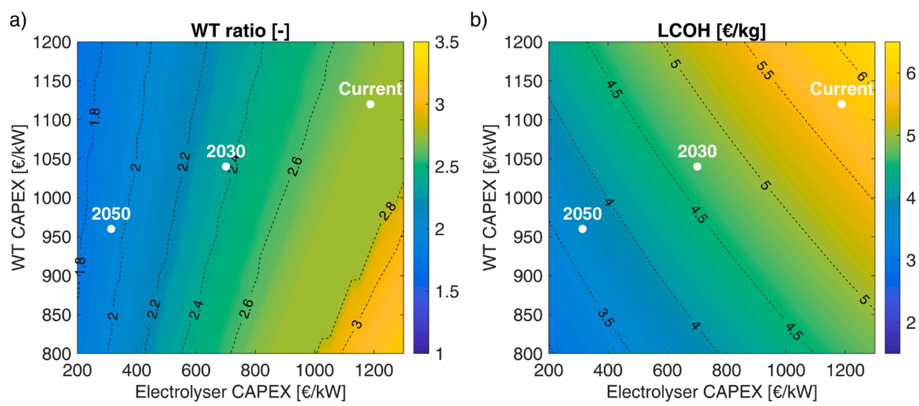

Fig. 10. WT-only configuration: (a) WT ratio and (b) LCOH as a function of the CAPEX of electrolyser and WT. Current, 2030 and 2050 cost scenarios are based on the data shown in Table 2.

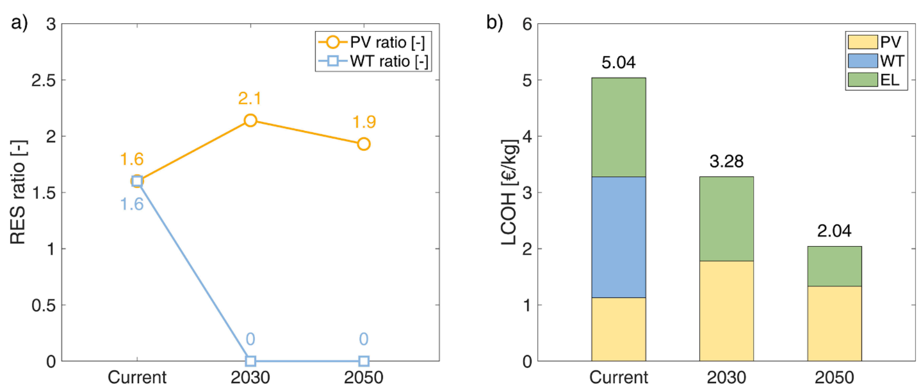

Fig. 11. Hybrid configuration: RES ratios and LCOH in the current, 2030 and 2050 cost scenarios (defined in Table 2).

described for the PV-only configuration. Therefore, the WT technology is penalised by the limited CAPEX reduction and is not included in the future optimal configurations.

This trend was also observed by IRENA in [23], where the authors pointed out that – under 2050 cost assumptions – PtH systems will most likely reach the minimum LCOH when operating as a solar PV-only configuration. The LCOH for the hybrid configuration (Fig. 11b) decreases from 5.04 €/kg in the current scenario to 3.28 and 2.04 €/kg in the 2030 and 2050 scenarios, respectively. Since the optimal hybrid configuration in 2030 and 2050 only includes the PV technology, the LCOH values in these scenarios are the same as those of the PV-only configuration (highlighted in white in Fig. 9). A WT CAPEX lower than about 550 €/kW would be required to make a hybrid PV-WT configuration cheaper than a PV-only configuration (considering the PV cost assumption for 2050). The energy and economic indicators for all configurations (PV-only, WT-only and hybrid) in the current and future cost scenarios are also available in the Supplementary Material. It is worth noting that the results presented here derive from a purely economic optimisation. However, the hybridisation of renewable electricity production could be necessary if other parameters – such as the installable potential of renewable resources and the extent and location of the hydrogen demand – are taken into account. Moreover, the results of this study refer to a renewable-based PtH system aimed at maximising hydrogen production with no contraints on the hydrogen demand.

Finally, the impact of the battery storage cost on the optimal design of the PtH system was examined using the battery cost projections shown in Table 2. For both 2030 and 2050 cost projections, the battery is not included in the cost-optimal solution and the results are therefore not reported as they are the same as those previously discussed for the configurations without battery. Similar to the current scenario (Table 3), the inclusion of battery storage in the 2030 and 2050 scenarios proves effective in improving the U_{EL} indicator; however it does not result in economic benefits.

To sum up, the optimal size ratios are highly dependent on the costs of the technologies involved in the PtH system, i.e. PV, WT and electrolysers. The expected cost projections will reduce the production cost of green hydrogen to about 2 €/kg, making it increasingly competitive with grey hydrogen and conventional fossil fuels.

3.3. Implications of the study

The present section elucidates how this study aims to support industry and policy makers, by providing a methodological framework able to identify the cost-optimal (minimum LCOH) size ratio of a hydrogen production plant under variable boundary conditions (cost of the technologies).

Hydrogen has gained significant momentum in recent years, and dedicated national [40] and EU [41] incentives have been introduced to support the creation of hydrogen production hubs, hydrogen valleys and hydrogen applications in final uses [42]. In this context, it is essential to provide industrial users and stakeholders with guidelines on how to properly size new power-to-hydrogen plants. Given the high cost of the technologies involved, the design should aim for a cost-optimal layout in order to minimise the hydrogen production cost and enhance the competitiveness of low-carbon hydrogen in the market. Due to the specificities of each hydrogen plant, it is also crucial to show and elucidate the reasons behind the cost-optimal design point using a simplified and replicable methodology. This approach enables players entering the hydrogen market to leverage the findings of this study in evaluating the cost-optimal design point for power-to-hydrogen systems, whether based on PV, wind or hybrid configurations. Additionally, this study is intended to support the development of policy instruments for the financing of hydrogen production plants. These instruments should aim at valorising and facilitating initiatives that involve plant configurations allowing for cost-competitive hydrogen production.

4. Conclusions

The main goal of this study is to optimise the design of renewable-based power-to-hydrogen (PtH) systems. Specifically, the research focuses on identifying the optimal combination of sizes for the RES generators and the electrolyser, with the aim of maximising hydrogen production at the minimum cost. The main reasons leading to the optimal size ratios are discussed through the introduction of energy and economic indicators. Different PtH configurations are explored, considering single-generator systems (PV-only and WT-only) and hybrid systems (both PV and WT). Additionally, the investment costs of PV, WT and electrolysers are varied to assess their potential impact on the optimal size ratios and the resulting LCOH.

The main conclusions can be summarised as follows:

- The utilisation of the renewable generator (U_{RES}) and the utilisation of the electrolyser (U_{EL}) exhibit opposite trends. By decreasing the RES ratio (i.e. ratio between the rated capacities of the RES generator and the electrolyser), the U_{RES} indicator improves, while the U_{EL} indicator decreases. On the contrary, when increasing the RES ratio, the electrolyser utilisation is maximised by penalising the use of the renewable generator. Depending on the costs of the technologies involved, the optimal solution tends to improve one of the two utilisation factors at the expense of the other.
- The optimal size ratio strongly depends on the investment costs for photovoltaics, wind turbines and electrolyser. A decrease in the RES investment cost (at fixed electrolyser CAPEX) increases the optimal RES ratio, while a decrease in the electrolyser investment cost (at fixed RES CAPEX) reduces the optimal RES ratio. When considering future cost scenarios, the optimal RES ratio is the result of the combined (and opposite) effect of reductions in both RES and electrolyser costs. Considering Italy as an example, the optimal PV ratio for the PV-only configuration is 2.2 in the current cost scenario. This value is expected to decrease to 1.9 in a future cost-scenario, indicating that the impact of electrolyser CAPEX reduction outweighs the reduction in PV CAPEX. Similar considerations apply to the WT-only configuration, wherein the optimal WT ratio decreases from 2.8 (current) to 1.9 (future). These optimal size ratios result in an LCOH of 5–6 €/kg, which will approach 2 €/kg in the future, making green hydrogen an increasingly cost-effective solution for decarbonising the hard-to-abate sectors.

Based on the methodology outlined in this study, future works will delve into examining the impact of solar and wind capacity factors (i.e. different geographical locations) on the optimal design of RES-based hydrogen production systems.

CRediT authorship contribution statement

Paolo Marocco: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marta Gandiglio:** Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Data curation, Conceptualization, Formal analysis. **Roberto Cianella:** Supervision, Project administration, Investigation. **Marcello Capra:** Supervision, Project administration. **Massimo Santarelli:** Writing – review & editing, Supervision, Project administration.

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.

Data availability

Data will be made available on request.

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Disclaimer: This paper was written with the personal contribution of two authors who work at the Ministry of Environment and Energy Security. The contents do not necessarily represent official positions of the Ministry.

Appendix A. Modelling of the battery energy storage

The main equations of the battery storage model are described below. At each time step, the energy stored in the battery ($E_{BT,t+1}$) can be computed based on the energy stored in the previous time step ($E_{BT,t}$) and the charging ($P_{BT,c,t}$) or discharging ($P_{BT,d,t}$) power [43]:

$$E_{BT,t+1} = E_{BT,t} + P_{BT,c,t} \cdot dt \cdot \eta_{BT,c} - \frac{P_{BT,d,t} \cdot dt}{\eta_{BT,d}} \quad (A.1)$$

where $\eta_{BT,c}$ is the battery charging efficiency and $\eta_{BT,d}$ is the battery discharging efficiency.

The battery charging power ($P_{BT,c,t}$ in Eq. (A.1)) was derived as the minimum of 3 different quantities [44]:

$$P_{BT,c,t} = min\left[\Delta_c, P_{BT,max,c}, \frac{(E_{BT,max} - E_{BT,t})}{dt \cdot \eta_{BT,c}}\right] \quad (A.2)$$

where Δ_c is the difference between the RES power ($P_{RES,t}$) and the electrolyser operating power ($P_{EL,in,t}$):

$$\Delta_c = P_{RES,t} - P_{EL,in,t} \quad (A.3)$$

The $P_{BT,max,c}$ term is the maximum charging power of the battery that depends on the C-rate parameter (C_{rate}), which is defined as the measure of the rate at which a battery is charged/discharged relative to its maximum capacity.

$$P_{BT,max,c} = C_{rate} \cdot E_{BT,rated} \quad (A.4)$$

Finally, the third quantity of Eq. (A.2) stands for the maximum charging power of the battery based on the energy currently stored in the battery ($E_{BT,t}$) and the maximum storable energy ($E_{BT,max}$). Specifically, the $E_{BT,max}$ term depends on the maximum SOC of the battery (SOC_{max}) as follows:

$$E_{BT,max} = SOC_{max} \cdot E_{BT,rated} \quad (A.5)$$

The battery discharging power ($P_{BT,d,t}$ in Eq. (A.1)) can be derived according to the following expression [44]:

$$P_{BT,d,t} = min\left[\Delta_d, P_{BT,max,d}, \frac{(E_{BT,t} - E_{BT,min}) \cdot \eta_{BT,d}}{dt}\right] \quad (A.6)$$

where $P_{BT,max,d}$ is computed in the same way as $P_{BT,max,c}$ (i.e. through Eq. (A.4)), and Δ_d is given by the difference between the electrolyser rated power ($P_{EL,rated}$) and the RES power ($P_{RES,t}$):

$$\Delta_d = P_{EL,rated} - P_{RES,t} \quad (A.7)$$

Finally, the third element of Eq. (A.6) is the maximum discharging power of the battery based on the energy currently stored in the battery ($E_{BT,t}$) and the minimum storable energy ($E_{BT,min}$). The $E_{BT,min}$ can be expressed as a function of the minimum SOC of the battery (SOC_{min}) as follows:

$$E_{BT,min} = SOC_{min} \cdot E_{BT,rated} \quad (A.8)$$

The technical parameters adopted for the modelling of the battery component are reported in Table 1.

Appendix B. Influence of the sale price of surplus power on the design of the power-to-hydrogen system

The net present cost of the PtH system (C_{tot}, in €) was updated by considering the revenues from the sale of surplus power (with i = PV, WT, BT, EL):

$$C_{tot} = \sum_i \left[C_{capex,i} + \sum_{n=1}^{N} \frac{C_{opex,tot,i,n} - C_{SU,n}}{(1+z)^n}\right] \quad (B.1)$$

where $C_{capex,i}$ is the investment cost of component i, $C_{opex,tot,i,n}$ is the total operating cost of component i during year n, $C_{SU,n}$ is the revenue for the sale of electricity during year n, N is the lifetime of the project, and z is the discount rate. The $C_{SU,n}$ term was computed as follows:

$$C_{SU,n} = \sum_{t=1}^{T} (c_{sell} \cdot P_{SU,t} \cdot dt) \quad (B.2)$$

where c_{sell} (in €/kWh) is the sale price of electricity, $P_{SU,t}$ (in kW) is the surplus power in time step t, and dt (in h) is the duration of the time step.

Concerning the PV-only configuration (Fig. B.1), the LCOH decreases as the sale price of electricity increases. An increase in the sale price from 0 to 0.04 €/kWh leads to an increase in the optimal PV ratio from 2.2 to 4.6. Moreover, with sale prices above about 0.04 €/kWh, the LCOH always decreases with increasing PV ratio, i.e. it becomes economically convenient to install as much PV as possible to enhance the electricity production. However, it is worth noting that the optimal solution entails a worsening of the U_{RES} indicator as the electricity sale price increases (Fig. B.1b), which means that the fraction of RES energy that is converted into hydrogen is reduced. Therefore, the system gradually moves away from a power-to-hydrogen business case since the generator is oversized to sell electricity (electricity-driven business case).

Similar considerations remain valid for the WT-only configuration (Fig. B.2), where the optimal WT ratio increases and the U_{RES} indicator decreases as the sale price increases.

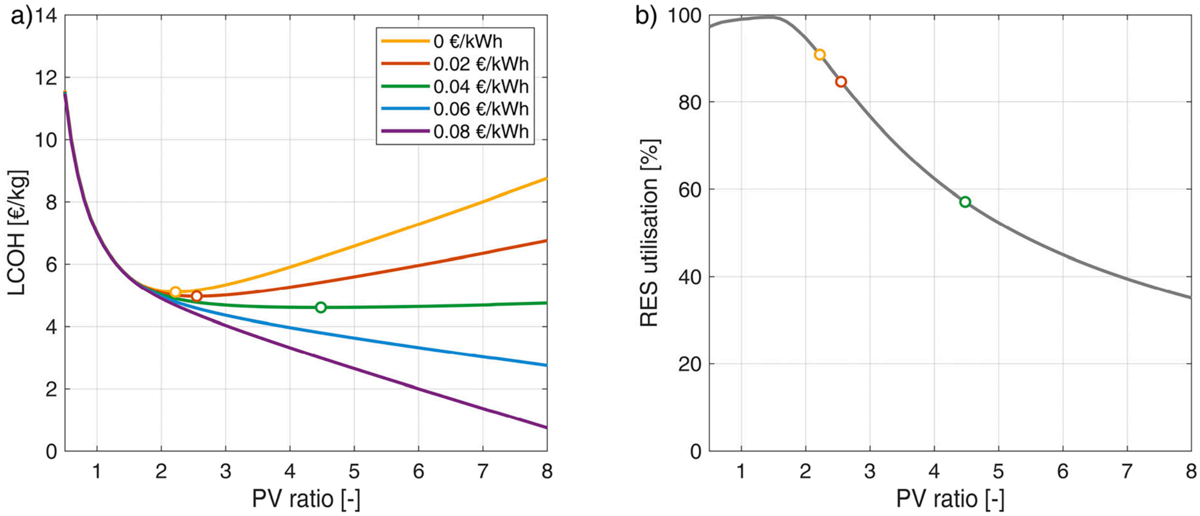

Fig. B1. PV-only configuration: a) LCOH as a function of the PV ratio, b) RES utilisation as a function of the PV ratio. The cost-optimal design points are marked with dots. Results refer to the current cost scenario.

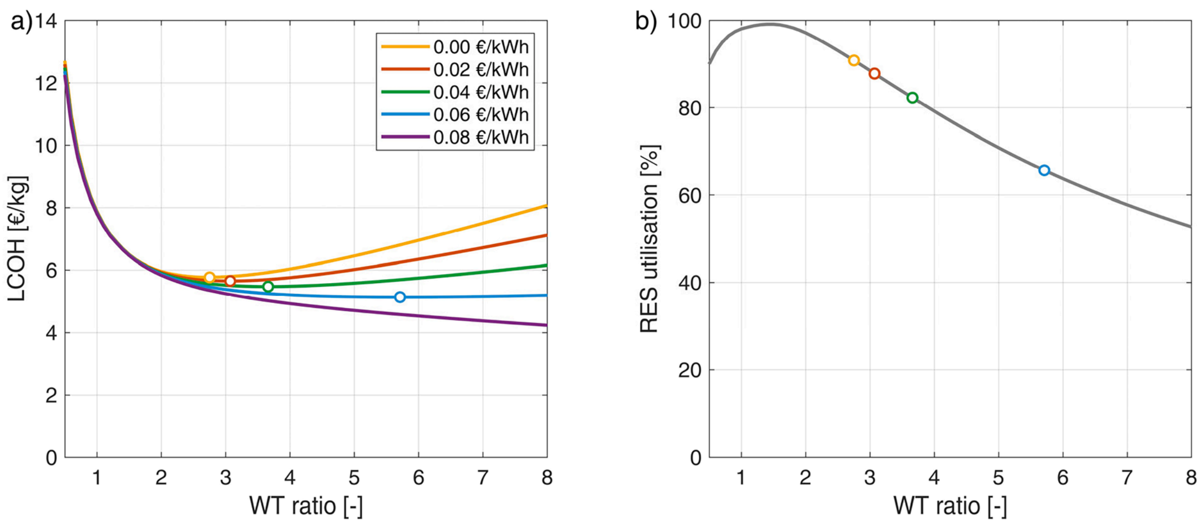

Fig. B2. WT-only configuration: a) LCOH as a function of the WT ratio, b) RES utilisation as a function of the WT ratio. The cost-optimal design points are marked with dots. Results refer to the current cost scenario.

Appendix C. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enconman.2024.118646.

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