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Water electrolysis powered by renewables: Optimising the cost of green hydrogen production across Europe

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Abstract

Depending on the end-use application, electrification may not always be technically feasible or the most cost-effective option. In particular, industries with substantial challenges in decarbonisation, such as hard-to-abate sectors (e.g., steel, cement, fertilizer) and heavy-duty transport (e.g. trucks, maritime, aviation) necessitate alternative solutions. In this context, hydrogen or hydrogen-derived fuels play a crucial role in the transition away from fossil fuels.

At present, the most promising way to produce low-carbon hydrogen is water electrolysis powered by renewable energy sources. Achieving a cost-optimal design of the power-to-hydrogen (PtH) system, encompassing both renewable energy generators and electrolysers, is essential for delivering green hydrogen at the lowest possible cost. In this work, renewable-based PtH systems are designed with the aim of reliably fulfilling a specified hydrogen demand profile, while concurrently minimising the cost of hydrogen production. The optimal design problem is solved utilising the mixed integer linear programming technique. Specifically, both the sizes of the PtH components (i.e., renewable generators, electrolyser and hydrogen storage) and their operation over time are set as decision variables. Special attention is also given to accurately modelling the electrolyser behaviour, by implementing a real partial-load performance curve for the electrochemical device, constrained within an appropriate modulation range.

A European-scale assessment is conducted with the ultimate goal of investigating how wind and solar resources influence the optimal design of the PtH system. The levelised cost of hydrogen (LCOH) is found to vary across a wide range, spanning from 5 €/kg to more than 20 €/kg, depending on the PtH configuration and geographical location. The study highlights the importance of hybridising renewable production in limiting the oversizing of the PtH components, thereby ensuring favourable LCOH values.

Introduction

Hydrogen is currently gaining unprecedented momentum, marked by a rapid increase in the number of hydrogen-related policies and projects worldwide [1]. Presently, hydrogen serves various essential roles: as a feedstock for chemical production (such as ammonia and methanol), as a reducing agent in steelmaking, and for the purification and upgrading of heavy oil fractions in refineries. Moreover, it is expected to play a pivotal role in expediting the transition towards a carbon-neutral future. Indeed, in a decarbonised society, hydrogen and its derivatives will fulfil a wide range of applications, including heavy-duty transport such as shipping and aviation [2], the chemical industry [3], high-grade heat generation [4], and long-term energy storage [5].
In this context, it becomes essential to provide low-carbon hydrogen at the lowest possible cost, making it competitive with fossil fuel-based routes (i.e., natural gas and coal), which currently dominate the global hydrogen production [6]. However, because of the fluctuating behaviour of solar and wind energy, new challenges emerge in guaranteeing a reliable and cost-effective supply of green hydrogen.
In this work, an optimisation framework is developed to address the cost-optimal design of hydrogen production systems powered by renewable energy sources. In contrast to the existing literature on this topic, which typically focuses on specific case studies, the present work extends the analysis to several European countries. The goal is to assess how wind and solar resources influence the optimal design of the power-to-hydrogen (PtH) system and the hydrogen cost. In order to identify the most cost-effective solution for each country, the European-scale assessment also covers various system configurations based on the type of renewable generator: photovoltaic (PV)-only, wind turbine (WT)-only and hybrid (i.e., both PV and WT).

1. Materials and methods

Figure 1 shows the layout of the PtH system analysed in this work. The electricity that powers the electrolyser comes from a photovoltaic and/or wind system. A hydrogen storage system is also included to provide flexibility and reliably cover the hydrogen demand of the end-user.

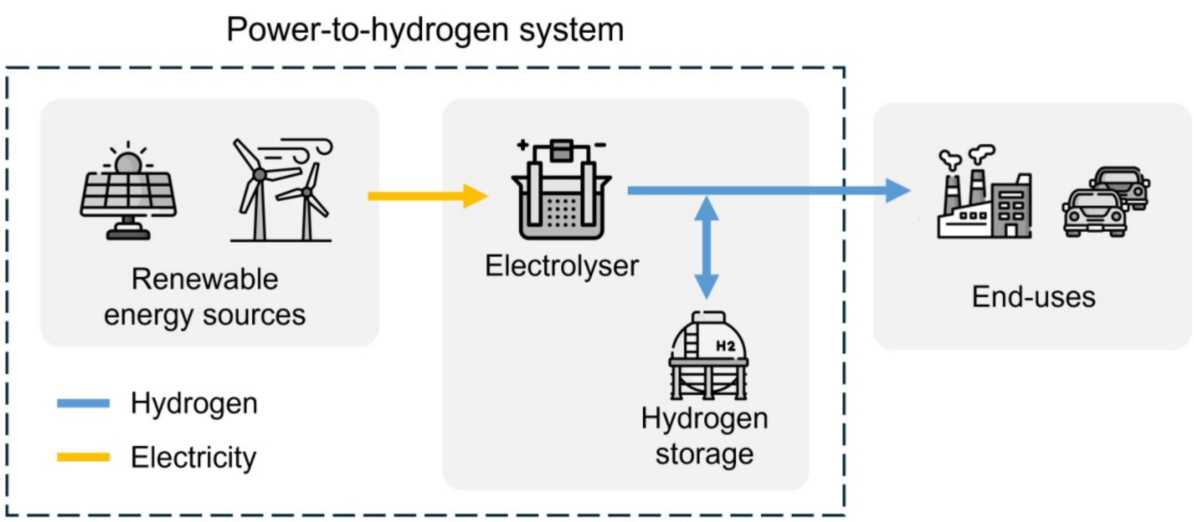

Figure 1. *Layout of the power-to-hydrogen system.*

An optimisation framework – based on the mixed integer linear programming (MILP) technique – was developed to address the optimal design of renewable-based hydrogen production systems. The levelised cost of hydrogen (LCOH) was used as objective function of the optimisation problem. Specifically, the aim is to cover the hydrogen demand of the end-user for each time step (t) of the time horizon (T), while simultaneously minimising the LCOH. The simulation was carried out over a year-long time horizon with hourly resolution.

As schematised in Figure 2, the primary inputs to the MILP-based optimisation process are as follows:

1. The techno-economic data (e.g., investment costs, operation & maintenance costs, modulation range, efficiency curve) associated with all components of the PtH system.
2. The hydrogen demand profile $\forall\, t \in T$.
3. The meteorological data, in terms of capacity factor (CF) profiles, of the photovoltaic and wind systems $\forall\, t \in T$.

The following decision variables are provided:

1. The optimal sizes of all components of the PtH system, i.e., photovoltaic, wind turbine, electrolyser and hydrogen storage.
2. The electrical power supplied to the electrolyser (input) and the hydrogen power generated by the electrolyser (output) $\forall\, t \in T$.
3. The surplus renewable power not supplied to the electrolyser $\forall\, t \in T$.
4. The charging and discharging power of the hydrogen storage $\forall\, t \in T$.
5. The quantity of energy stored in the hydrogen storage $\forall\, t \in T$.

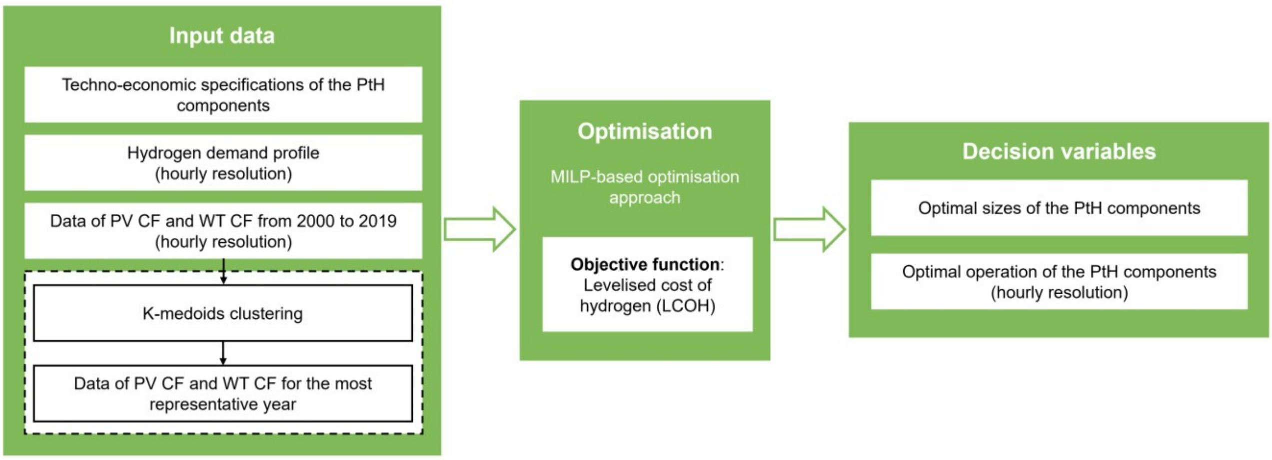

Figure 2. *Optimisation framework for the optimal design of power-to-hydrogen (PtH) systems.*

A detailed description of the optimal design methodology can be found in [7]. In the present study, it is further expanded to improve the robustness in estimating the electricity production from renewable energy sources. Specifically, country-aggregated time series of PV and WT capacity factors from the year 2000 to 2019 were taken from [8]. As shown in Figure 2, the k-medoids clustering technique was then applied to pinpoint the most representative year, which was then used as input to the optimisation framework. This process was repeated for all European countries with the goal of evaluating the optimal LCOH as solar and wind availability varies.

The LCOH was computed according to the following expression (in €/kg):

$$LCOH = \frac{CAPEX_0 + \sum_{j=1}^{N} \frac{OPEX_j + REP_j}{(1+d)^j}}{\sum_{j=1}^{N} \frac{M_{H_2}}{(1+d)^j}} \tag{1}$$

where $CAPEX_0$ are the total capital expenditures occurring at the beginning of the analysis period (i.e., j=0), $OPEX_j$ are the total operation and maintenance costs of the PtH system during the j-th year, REP_j are the total replacement costs of the PtH system during the j-th year (for a given component, replacement costs are null if it does not need to be replaced in that year), M_{H_2} is the amount of hydrogen produced annually by the PtH system, d is the discount rate, and N is the project lifetime.
For an accurate representation of the partial-load performance of the electrolyser, a real efficiency curve was also implemented within the MILP framework. In particular, a proton-exchange membrane (PEM) electrolyser was considered, given its good compatibility with variable renewable energy sources. The list of all techno-economic assumptions, along with the electrolyser efficiency curve, is reported in [7].
In this work, the hydrogen demand profile was set constant to reflect a typical industrial process. Indeed, the demand for hydrogen in heavy industrial applications, such as the steelmaking process and ammonia production, typically remains steady over time [9].

2. Results and discussion

The average annual capacity factors of PV and WT are shown in Figure 3. For each European country, they refer to the most representative year, which was computed according to a clustering procedure of country-aggregated CF time series from 2000 to 2019. The average PV capacity factor spans from 10% (Finland) to 19% (Cyprus); whereas a broader range is found for wind farms, from 7% (Slovenia) to 30% (Finland).

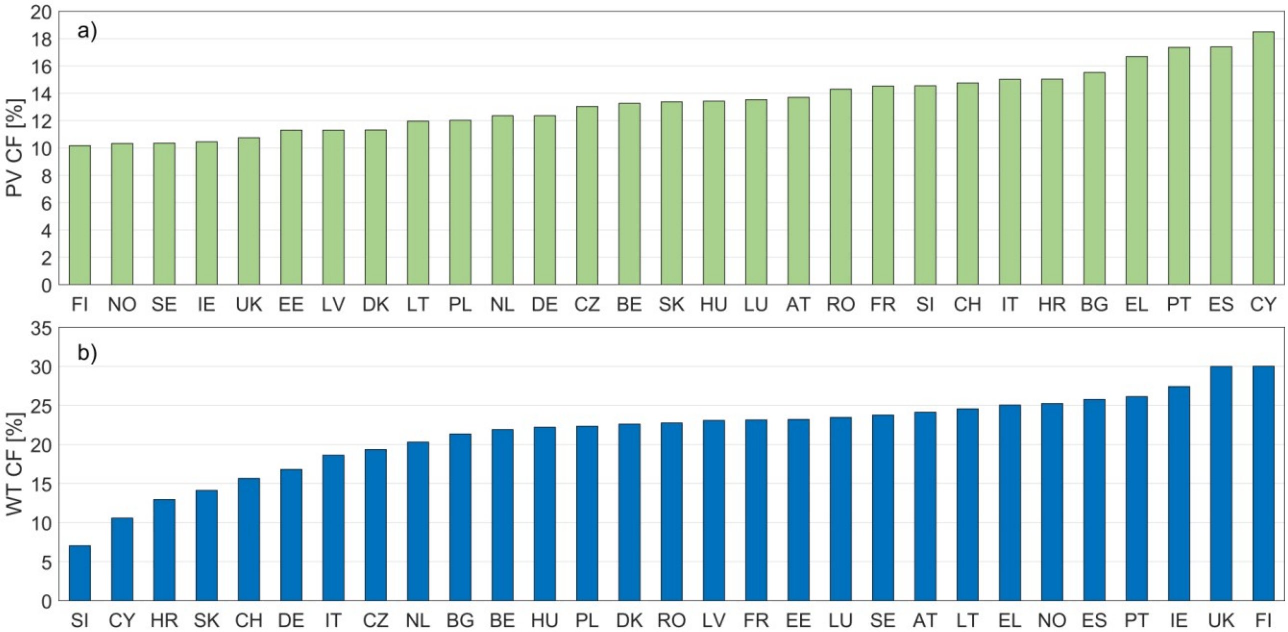

Figure 3. *a) Average annual capacity factor of photovoltaic (PV CF) and wind turbine (WT CF) for different European countries. Acronyms of the European countries are provided in the Nomenclature section.*

Based on the identified hourly profiles of PV and WT capacity factors, the optimal design of the PtH system was conducted for different European countries, considering a steady hydrogen demand profile over the year. Figure 4 shows the resulting LCOH values for the various PtH configurations (i.e., PV-only, WT-only and hybrid).

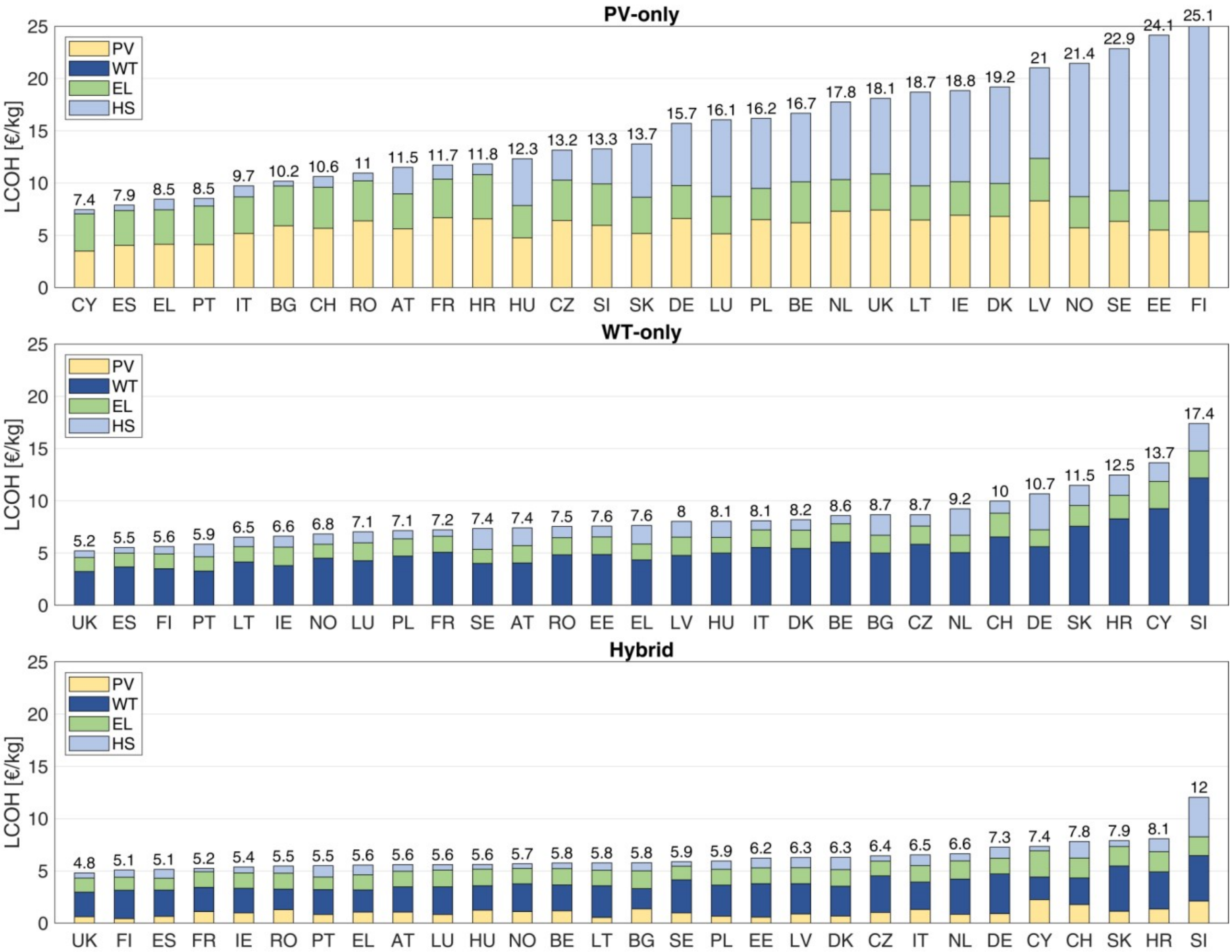

Figure 4. *LCOH breakdown of the PV-only, WT-only and hybrid configurations for different European countries.*

Examining the results of the PV-only scenario, the LCOH is in the range of 7.4 to 25.1 €/kg, depending on the PV capacity factor. It is worth noting that, moving to countries with lower PV availability, the cost of hydrogen increases mainly due to a sharp rise in the contribution associated with the hydrogen storage system. Specifically, geographical locations with an average PV CF below approximately 13% necessitate large-scale hydrogen storage systems (approximately 500 to 2000 hours of autonomy), which significantly impacts the final cost of hydrogen. For instance, in regions with limited availability of solar resource – such as Norway, Sweden, Estonia and Finland – over half of the LCOH is attributed to the hydrogen storage section.

Despite the higher specific cost of wind turbines (1120 €/kW) compared to PV (650 €/kW), the LCOH for WT-only systems, which ranges from 5.2 to 17.4 €/kg, is lower than that of PV-only systems (expect for Croatia, Cyprus and Slovenia). Indeed, WT-only configurations generally require less oversizing of the electrolyser and hydrogen storage (with respect to the average hydrogen demand to be covered), and also enable better exploitation of the local renewable resource.

Finally, hybridising the renewable production is highly effective in limiting the oversizing of PtH components (i.e., renewable generators, electrolyser and hydrogen storage). As can be seen from Figure 4, for all European countries, deploying both PV and WT emerges as the most favourable solution, with an LCOH that spans from 4.8 to 12 €/kg. The hybrid solution achieves an average LCOH reduction of 52% compared to the PV-only configuration and 23% compared to the WT-only configuration.

3. Conclusion

A European-scale assessment was conducted to investigate the influence of renewable energy sources on the optimal design of hydrogen production systems. To this aim, an optimisation framework, based on the mixed integer linear programming technique, was developed. In addition, a clustering procedure was implemented to pinpoint the most representative year from a multi-year time series.
Depending on the European country, the LCOH varies across a wind range, spanning from about 5 to over 20 €/kg. In PV-only systems (7.4-25.1 €/kg), the hydrogen storage emerges as a significant cost contributor (above 30%) when the average annual PV capacity factor falls below approximately 13%. Compared to PV-only systems, WT-only configurations typically necessitate less oversizing of the electrolyser and hydrogen storage, resulting in lower LCOH values (5.2-17.4 €/kg). Finally, for all European countries, hybridising the renewable production emerges as the optimal solution for delivering green hydrogen at the lowest cost (4.8-17.4 €/kg). Future works will further delve into this assessment for evaluating size and cost correlations as a function of the geographical location.

Acknowledgment

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Nomenclature

AT	Austria
BE	Belgium
BG	Bulgaria
CF	Capacity factor
CH	Switzerland
CY	Cyprus
CZ	Czechia
DE	Germany
DK	Denmark
EE	Estonia
EL	Greece
ES	Spain
FI	Finland
FR	France
HR	Croatia
HU	Hungary
IE	Ireland
IT	Italy
LCOH	Levelised cost of hydrogen
LT	Lithuania
LU	Luxemburg
LV	Latvia
NL	Netherlands
NO	Norway
PEM	Proton exchange membrane
PL	Poland
PT	Portugal
PtH	Power-to-Hydrogen
PV	Photovoltaic
RO	Romania
SE	Sweden
SI	Slovenia
SK	Slovakia
UK	United Kingdom
WT	Wind turbine

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