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Doctoral Dissertation  
Doctoral Program in Energy Engineering (37<sup>th</sup> Cycle)

# **The adoption of renewable hydrogen for a cost-effective decarbonization of hard-to-abate industries**

Development of an optimization framework for the  
cost-optimal design of power-to-hydrogen systems

**Davide Trapani**

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**Supervisor**

Prof. Massimo Santarelli

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# Summary

Renewable hydrogen is widely considered as a key enabler of the global energy transition, and it can play a crucial role in the decarbonization of hard-to-abate industries. At present, hydrogen demand for industrial processes exceeds 97 Mt per year and is largely met by unabated steam methane reforming (SMR) and coal gasification, which ensure low-cost hydrogen supply while causing the emission of more than 900 Mt<sub>CO2</sub>. It is thus evident that a radical transformation in the hydrogen production pathways is crucial. In this context, renewable power-to-hydrogen (P-t-H) systems thus emerge as a promising route for producing carbon-neutral hydrogen by exploiting renewable electricity to drive the water electrolysis process. Currently, several electrolysis technologies are available on the market, ranging from mature solutions such as alkaline (AEC) and proton exchange membrane (PEM) electrolyzers to more innovative but less commercially proven alternatives like anion exchange membrane (AEM) and solid oxide (SOEC) electrolyzers. However, replacing fossil-based hydrogen in hard-to-abate industries remains economically challenging due to the higher production cost of renewable hydrogen, mainly driven by electricity cost and capital-intensive electrolyzers. In addition, the adoption of renewable hydrogen is still hindered by technological limitations related to electrolyzer durability, particularly when coupled with variable renewable sources. Furthermore, the steady hydrogen consumption profile of hard-to-abate industries typically requires the adoption of storage systems to manage the potential intermittency of renewable hydrogen production. The cost-optimal design of P-t-H systems is therefore essential to ensuring cost-competitiveness, environmental sustainability and reliability of renewable hydrogen. This study thus combines detailed modelling of hydrogen production, handling, storage and transport technologies with an optimization

framework based on metaheuristic algorithms. Integrated electrochemical and techno-economic models of low- and high-temperature electrolyzers (AEC, PEM, AEM and SOEC) are implemented, including performance data of real systems, size-dependent cost functions and accurate lifetime estimation. In addition, renewable electricity generation from solar and wind is modeled, and power purchase agreement (PPA) mechanisms are defined by considering country-specific prices. Finally, detailed cost estimation methodologies are developed for hydrogen production via SMR (accounting for plant capacity, natural gas price and CO<sub>2</sub> emissions cost) and hydrogen transport by trucks (both as compressed and liquid) and newly built pipelines. The particle swarm optimization (PSO) algorithm combined with a rule-based energy management strategy is adopted for the cost-optimal sizing of the P-t-H systems, while the  $\epsilon$ -constraint technique is employed to explore different decarbonization targets. The proposed methodology is applied to assess the cost-competitiveness of adopting renewable P-t-H systems to replace fossil-based hydrogen in three real industrial case studies: a semiconductor manufacturing plant, a float glass production site and an oil refinery. The results of the different case studies confirm that conventional SMR-based hydrogen production remains the most cost-effective supply option, although fluctuations in natural gas prices can significantly affect its cost-competitiveness and its carbon intensity is inconsistent with the achievement of long-term climate goals. On the contrary, P-t-H systems relying on both on-site renewable power production and PPA-based electricity ensure carbon-neutral hydrogen supply, while still exhibiting higher production costs. Although not yet cost-competitive, the adoption of renewable hydrogen is essential for reducing industrial emissions and supporting the transition to a low-carbon economy. Securing low-cost electricity (below 50 €/MWh) can narrow the gap with fossil-based hydrogen. Alternatively, more stringent carbon pricing mechanisms aligned with the long-term projections reported in global energy policies are required for renewable hydrogen to reach the cost-parity with SMR. Hydrogen delivery via large-scale pipelines offers the lowest transport cost but infrastructural barriers and market uncertainties have to be overcome for its widespread adoption. Compressed hydrogen delivery proves to be suitable only for short transport distances (below 170 km) due to its limited payload capacity. Conversely, liquid hydrogen supply becomes more cost-efficient over longer transport ranges, but it requires low electricity prices to drive the energy-intensive liquefaction process.