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PHOENIX

Low-carbon Hydrogen Production via Intensified (photo-) reactors and waste sources

Executive Summary

Hydrogen is emerging as the future of renewable fuels, with various technologies for its production under development. Upon alternative solutions, photocatalysis stands for its unique potentialities: reduced electric energy consumption, simple and robust reactors. Moreover, green hydrogen production is combined with purification of industrial wastewater, making this technology doubly appealing.

Currently, no commercial photocatalysis reactors for hydrogen production are available. Furthermore, the literature reports mainly photocatalysis reactors performing water-splitting and does not use wastewater. The PHOENIX project is indeed aiming at investigating the hydrogen cost of a photocatalysis pilot plant. In fact, before realizing an industrial-size plant, it is essential to establish on a smaller scale the competitiveness of the technology. A techno-economic analysis has been therefore conducted, from which the following major findings can be drawn.

1. **Hydrogen cost of 63 €/kg.** Competitive technologies deliver similar order of magnitude performance. Small photovoltaic–electrolyser plants, comparable to the PHOENIX pilot one, are characterized by a price around 30 €/kg. The current estimate for PHOENIX, although higher, is only preliminary and could be rapidly improved. On the other hand, subsequent large industrial plants should face a lower competitor's price, around 12 €/kg. Currently, it is not possible to estimate how an industrial size photocatalysis plant would perform compared to alternative technologies.
2. **Wastewater purification and valuable chemical production.** Currently, green hydrogen is produced mainly by water splitting, which, starting from pure water, generates hydrogen and valueless oxygen. PHOENIX reactor uses wastewater instead, with two clear advantages. Firstly, at the end of the process, water is purified. This peculiarity makes the technology suitable in the wastewater treatment environment, which is in constant growth due to tightening of EU/Italian discharge standards. Secondly, the products are hydrogen and valuable chemicals rather than oxygen, with increased economic yield of the plant.
3. **Continuity of operation.** Photocatalysis is sun based, with little electrical energy required for the pumps and separation systems. However, if round the clock hydrogen production is required, the PHOENIX reactor can include a LED lamp, which can provide the required ration energy necessary during night hours.

The potentialities of a photocatalysis reactor, combined with its modular and therefore scalable and adaptable design, make it suitable for a wide range of industrial fields. In fact, scaling the PHOENIX pilot plant up to industrial size plants does not require any change in the architecture. Smaller reactors are more indicated for the agricultural field such as wineries, while greater plants can fit larger comapanies needs, from food and beverage to refineries.

The project is now at a point where further steps are needed before realizing commercial plants:

1. **Experimental campaign.** The analysis is currently based on limited empirical results. It is essential to perform a more structured experimental campaign, to fully characterize the performance of the reactor product under all the possible operative conditions.
2. **More insights from industries.** The chemical reaction performed depends on the union of catalyst and the chemical composition of the wastewater, which in turn depends on the industrial application. Thus, it is crucial to build a reasoned map of potential users, to direct the design toward the industrial applications with the highest likelihood of success.
3. **Real size plant.** Too many variables contribute to the cost and production rate of hydrogen and it is impossible to model all of them. It is essential to build a real pilot plant to assess the effectiveness of the predictions before proceeding with a scale-up, eventually correcting the model.

PHOENIX pilot plant shows different characteristics from water splitting by electrolysis. Currently, the design of the reactor has just been patented by Snam (WO2025045776A1). Based on a strategic analysis of external market dynamics and Snam internal capabilities, the recommended go to market model is patent licensing. Once the projected performances are validated through full-scale pilot plants and experimental campaigns, the resulting dataset will provide a robust basis for partner selection and contractual terms, and can be distilled into a concise licensing package. This pathway enables disciplined commercialization while preserving strategic flexibility.

Key words: Photocatalysis, Green hydrogen, Waste water recycling, Cost analysis

PHOENIX

energy from waste

Project description written by the Principal Academic Tutor

The current project proposal aims to lay out a continuation of ongoing R&D projects from the Decarbonisation Unit of Snam. More specifically, the projects related to other modes of hydrogen production with respect to conventional electrolysis, namely the (bio-) hydrogen generation along with value-added oxidative half-reaction. The approach being developed relates both to direct solar-to-hydrogen and de-coupled electrolysis, featuring process intensification approaches and novel reactor architectures. Remarkably, a patent has been submitted for a novel hydrid solar/artificiallighting photo-reactor. Consequently, key project goals are represented by 1) a techno-economic analysis of bio-hydrogen production from wastewaters or waste materials, 2) the definition of a product development roadmap for a solar photo-reactor and 3) a market analysis of major sources of industrial waste streams that can be valorised. The themes of innovation range from novel engineering approaches to hydrogen production and waste management, as well as new business model to be explored for the valorisation of the IP. The multi-disciplinarity of the projects therefore stems from the combination of circular economy, low-carbon hydrogen production and the related policy scenarios that are currently being defined. Finally, potential beneficiaries are represented by industries with liquid waste streams and the whole hydrogen value chain.

Team description by skill

The ASP PHOENIX team is composed of seven MSc students, divided into two main groups:

- **The Market Analysis group** focused on investigating the economic context surrounding existing green hydrogen production technologies and companies, with a particular emphasis on Snam core business. After outlining the main advantages and limitations of photocatalysis, the team identified potential future stakeholders and developed feasible go-to-market strategies aimed at maximizing the impact of the technology across various sectors. The sub-team is composed of:
  - Giorgio Gueli
  - Duccio Profeti
  - Giovanni Tomasella

  They share academic expertise in the fields of Business and Management.
- **Techno-Economic Analysis group** was responsible for estimating the cost of photocatalytic hydrogen production in order to assess the competitiveness of the technology. To this end, a study reactor was modeled and its main equipment defined. Furthermore, reaction data provided by StarLIGH2T, a core project partner, was analyzed to extract key reaction performance parameters. A Matlab code was also developed to evaluate typical direct and indirect costs associated with the implementation of a photocatalytic plant. The sub-team is composed of:
  - Emanuela Loffredo
  - Alessia Rossi
  - Filippo Giacomoni
  - Francesco Ceglie

  They bring together diverse academic backgrounds in Chemistry, Physics, and Thermodynamics as well as developed expertises in programming.

Goal

The PHOENIX project aims to lay the foundations for the next generation of green hydrogen production technologies. By leveraging photocatalysis, Snam intends to bring to life a new concept of reactors capable of overcoming the current limitations of electrolysis.

At present, this promising but still unexplored approach lacks essential experimental data and strategic market assessments required to envision a breakthrough industrial implementation. Therefore, the goal of the PHOENIX project is to gather both technical and market insights to take a decisive step forward in this highly attractive field.
The project pursues two main objectives:

- Assess the competitiveness of the technology by evaluating the cost of photocatalytic hydrogen production and analyzing the design features of a reactor plant that can be effectively deployed in industrial settings. At the same time, this analysis wants to integrate meaningful experimental data to provide a more reliable estimation.
- Identify potential technology stakeholders in order to define the most suitable strategic development path and propose a go-to-market strategy for the intellectual property owners, thereby maximizing the return on technological know-how and its impact on future market and society.

As a result, it is clear how the research purpose was not only to estimate costs but also to understand where and how this technology could offer unique advantages.

Understanding the problem

The transition towards a low-carbon economy increasingly relies on green hydrogen as a versatile energy carrier for hard-to-abate sectors such as refining, chemicals, and heavy transport. While water electrolysis powered by renewable electricity represents the current benchmark for sustainable hydrogen production, it presents significant limitations: the process requires high-purity water, involves energy-intensive steps, and produces oxygen as a largely valueless by-product. Moreover, electrolysis is capital-intensive and depends on fluctuating electricity costs, challenging its competitiveness.

At the same time, wastewater management is an increasingly pressing environmental and regulatory challenge. Dominant industrial sectors generate large volumes of effluents rich in organic pollutants. Meeting the progressively stricter EU discharge limits often requires multi-step treatments, which are energy intensive, generate sludge, and incur high operating costs. This creates both an environmental burden and an economic challenge for operators.

Photocatalysis emerges as a promising technology that can address both problems simultaneously. By using solar-driven catalysts, organic-rich wastewater streams can be treated while producing hydrogen and other valuable chemicals.
Despite its potential, photocatalytic hydrogen production remains at an early stage. Existing demonstrations are limited to laboratory batch reactors, with efficiencies lower than those of electrolysis. No industrial-scale plants are currently in operation, and many techno-economic variables, such as reaction performance under real wastewater conditions, scalability of reactor design, and the value of chemical co-products, remain uncertain.

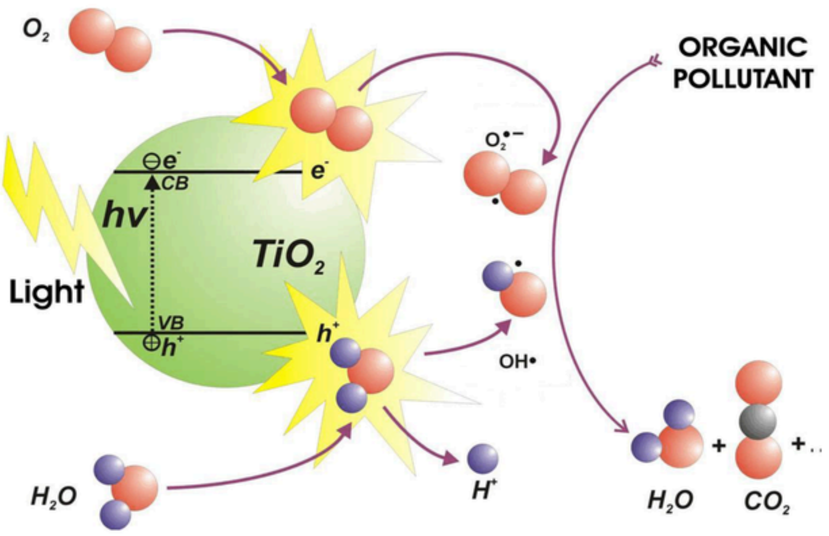
Exploring the opportunieties

Many industries today generate effluents rich in organic compounds, which are costly to treat and subject to increasingly strict regulation. At the same time, some of these very industries are among the largest consumers of hydrogen, relying on it for refining, chemical processes, or food production. This convergence makes them natural candidates for a technology that can transform a burden into a resource.

To better understand these opportunities, the economic dimension had to be considered. Gaining access to industrial data would have allowed to assess how wastewater streams could support hydrogen production and to model the costs more accurately. At first, a survey was designed and distributed to collect such information, but the number of responses was too limited to be useful. Attempts at direct contact followed, yet most companies explained that data on wastewater composition, volumes, or treatment costs were private and could not be disclosed. This lack of transparency is telling: it underlines the strategic importance of wastewater management in industry, while also confirming how difficult it is to evaluate new technologies without access to sensitive figures. In the absence of detailed company inputs, other sources of knowledge had to be relied upon to continue the analysis.

On the technical side, several options were explored to enhance the efficiency and applicability of the technology patented by Snam. First, it is noteworthy that photocatalysis encompasses various kinds of reaction. Although limited knowledge is currently shared within the scientific community regarding its actual industrial implementation, a substantial amount of performance data has been produced in recent years. For instance, extensively studied reactions include methanol, glycerol, and ethanol reforming, as well as the degradation of dyes and pharmaceuticals. Alongside the evaluation of reactant performance, the selection of an appropriate catalyst emerges as a key factor in unlocking the full potential of the reactions. Among the available options, the StarLIGH2T $AuTiO_2$ catalyst stands out for its distinctive characteristics, being capable of exploiting a broader portion of the solar spectrum, including parts of the UV and infrared regions, thus potentially increasing the reaction efficiency.

Thanks to the straightforward operating principle of photocatalytic reactors, such as the version patented by Snam, the required components and equipment are not particularly complex and can be manufactured with relative ease. Nevertheless, reactor scaling for cost estimation remains highly challenging due to the limited scientific knowledge regarding how configuration changes interact with varying wastewater volumes and how photocatalytic reactions perform under flow conditions.

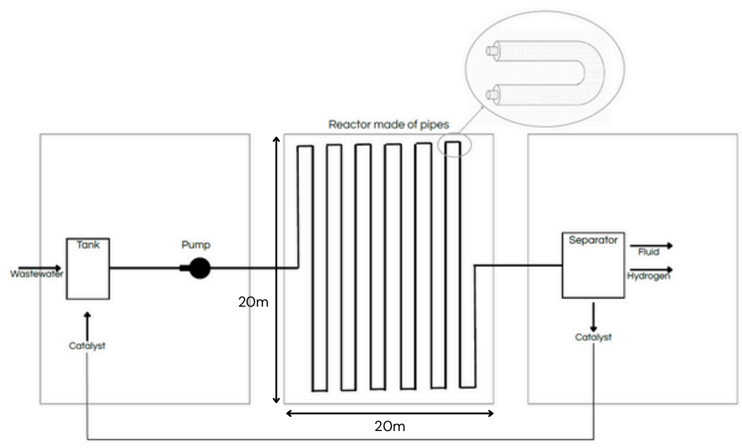


Photocatalysis reaction mechanism

Lastly, hydrogen production in photocatalytic reactors is directly dependent on light exposure. Limited daylight availability can significantly reduce performance, thereby lowering reactor efficiency. This limitation can be partially mitigated through the installation of LED lamps inside the reactor, as well as by adopting a modular reactor design that facilitates placement in the most sunlight-exposed areas of industrial facilities.

Generating a solution

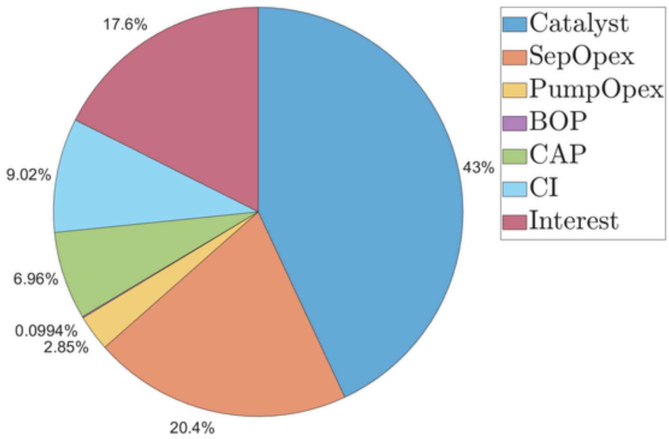
A reactor model was developed alongside its main equipment, designed with high modularity to accommodate future implementations and closely reflect its potential industrial configuration. This approach helped move beyond the batch experiments prevalent in academic literature, enabling the simulation of realistic operating scenarios using methanol-rich wastewater, a stream particularly relevant for wineries, agro-industrial facilities, and parts of the food-processing sector.



Reference reactor scheme

The main reactor array (20 × 20 m) consists of two concentric glass pipes forming separate shells that house distinct portions of the wastewater flow. The inner shell can accommodate LED lamps or an additional set of reactants and catalysts in future study cases. Differentiating photocatalytic reactions could further enhance hydrogen production by selecting appropriate catalyst pairs to fully exploit their solar absorption bands through a tandem mechanism, similarly to that used in multijunction photovoltaic panels.

Building on this foundation, a techno-economic model was implemented by adapting cost equations typically applied to electrolysis plants. Operating (Opex) and capital cost (BOP and CAP) items were extracted from the reactor model, while capital investment costs (CI) were estimated following the Peters and Timmerhaus methodology. Based on reaction performance data from the StarLIGH2T research group on methanol reforming with $AuTiO_2$ catalyst, the STC performance parameter was retrieved. This coefficient, which correlates hydrogen production with the total irradiance on the fluid, is essential in estimating photocatalytic hydrogen yield. Integrating these values into the techno-economic model led to a preliminary hydrogen production cost of 63 €/kg.



Hydrogen costs breakdown (Tot: 63 €/kg)

Given the inherent limitations of the techno-economic model, stemming from uncertainties in reactor facilities and discrepancies between operational conditions and experimental tests, a sensitivity analysis was conducted on reaction performance and reactor solar exposure. The results were then contextualized through a comparative analysis with other hydrogen production technologies. While existing photovoltaic–electrolyzer plants already achieve costs around 30 €/kg, setting a lower benchmark for green hydrogen, photocatalytic hydrogen remains promising. Sensitivity analysis highlights significant room for improvement, particularly regarding reaction performance, which could be enhanced in the short term by adjusting catalyst concentrations or selecting more efficient reactant–catalyst combinations.

The market analysis identified four sectors as promising entry points. Wastewater utilities face mounting costs and regulatory pressures, making them receptive to technologies that can reduce sludge and energy use. Refineries and petrochemical plants combine high hydrogen demand with complex effluents, positioning them as strategic early adopters. Wineries and agricultural producers generate methanol-rich waste streams that are particularly suited to photocatalysis, while food and beverage industries face tightening discharge limits and growing interest in sustainable branding. In each of these sectors, photocatalysis offers not just an environmental solution but a way to transform compliance costs into productive outputs.

Finally, the commercialization pathway has been addressed. Since the reactor design is already patented by Snam, the most suitable strategy is patent licensing. This model enables Snam to retain intellectual property control while collaborating with industrial partners for pilot deployments. Licensing provides scalability and risk-sharing, allowing external partners to invest in applications while Snam secures revenue streams and preserves strategic flexibility. Once validated through pilot plants and expanded experimental campaigns, licensing can provide a disciplined and credible route to commercialization without the heavy capital commitments of full-scale manufacturing.

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