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# Assessment of the green hydrogen chain value for port operations: A case of study in Chile

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## ABSTRACT

In Chile, the government presented the National Green Hydrogen Strategy, which will allow the export of this renewable fuel created with zero-emission energy, a positive contribution to carbon neutrality. This study addressed the possibility of integrating a green hydrogen value chain in the port sector. The study focused on generating electricity from photovoltaic solar energy to produce enough hydrogen in electrifiers to power a fuel cell that generated electricity and residual heat. Two scenarios were calculated for hydrogen generation depending on the solar energy available to cover an electrical and thermal demand in ports 1 $MWh_e$ and 0.1 $MWh_t$, respectively. For this purpose, the Calliope tool was utilized for energy system sizing. Furthermore, it was determined that the cost of 1 $kg_{H2}$ is 4.1 times higher than that of 1 liter of diesel to obtain the same 1 $MWh_e$. Similarly, the Levelized Cost of Energy was calculated for two operating conditions.

**Keywords:** green hydrogen, renewable energy resources, simulation energy systems, chain value

## 1. INTRODUCTION

The electric energy generated from Renewable Energy Systems (RES), mainly solar, wind, and geothermic, in 2021 represented more than 23% of the total energy generation of the National Electric System (SEN) for Chile [1]. Based on the total energy generated, the emission factor of the SEN was 0.3905 $tCO_{2eq}$/MWh for the year 2021. An option to reduce greenhouse gas emissions (GHG) and decarbonize the energy matrix appears in the "National Green Hydrogen Strategy in Chile" [2]. This strategy has played a fundamental role in just transitioning to developing sustainable and consuming a renewable fuels like the green hydrogen (green $H_2$).

Green $H_2$ allows the storage and the independent energy for specific processes in the industry [3,4], showing competitiveness over other technologies for reliability reasons or large storage volumes [5,6]. However, the techno-economic viability of green $H_2$ production depends on the country's specific resources and the characteristics of the energy market. Furthermore, the transport route, mode, and carrier significantly affect the supply chain's overall structure and the Levelized energy cost. Recently, studies by [7–9] place Chile as one of the largest producers of green $H_2$ worldwide and one of the international strategic routes for the commercialization of green $H_2$ together with other producers.

The green $H_2$ chain value green [10,11] studied links RES resources and the modernization of energy supply, transport, industry, and renewable energy export. Recently works [12,13] identified that the $H_2$-based energy system comprises four main stages, interconnected and interdependent [14], the generation, storage, safety or regulation, and final use of green $H_2$. The studies on these topics are diverse and mainly focus on empirical study and mathematical modeling to optimize the value chain [15,16]. It is also essential to know the behavior of this technology in the economy of the countries in a complex energy system [17]. Other studies have focused on specific applications [18,19]. The behavior of these systems using green $H_2$ has been shown to impact the case studies positively. Although its main disadvantage results in the high costs of the initial investment of the projects.

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The main objective of the work is to propose a complete value chain for the potential use of green $H_2$ produced from renewable energy (solar) in the electric and heat demand of a port in Chile. The dimensioning of the different technologies associated with green hydrogen allows for establishing the starting conditions for future scenarios in its national use. Furthermore, the originality and novelty lie in the object of study for a country whose future challenge is achieving energy independence in the global context and using simulation methodologies with different scenarios that allow the optimization of the energy system. In addition, obtain knowledge based on science and applied it to the local industry to develop the value chain of green hydrogen. In general, the results allow detailed information about the dependencies of a consumer and the renewable energy supplier through open-source models that predict the demand and available resources and the influence in the value chain for green $H_2$.

Finally, this study evaluates the consequences, effects, and short-term challenges for the final use of green $H_2$ in port operations, contributing to the country's energy transition to face climate change.

## 2. METHODOLOGY

The methodology consists of four essential steps. The first step is to identify the final consumers' energy demand according to their sectors of activity, such as electricity and heat. Secondly, the on-site renewable electricity generation was calculated from PV power energy based on the calculation tools of renewables.ninja for RES sources [20,21]. Third, a Proton Exchange Membrane Electrolyzer (PEM) for $H_2$ production ($kg_{H2}$) was defined due to its operational flexibility and the costs of such technology at the country level. Finally, the alternatives consider the direct consumption of the green $H_2$ in a Fuel Cell (FC) in which the generation of electrical energy and the residual heat produced with this equipment is used. The electric energy was used to cobber the final demand of the port operations and residual heat to produce hot water. Figure 1 shows the referential scheme of a value chain for the green $H_2$.

### *2.1 Input Data and Calculation Tools*

Due to a Non-Disclosure Agreement (NDA) established between the collaborating entities, it is impossible to mention the installation studied explicitly. Therefore, the load demanded by the total end consumers of the green $H_2$ within the study port was established generically, which can be extended if necessary.

The calculation was developed using the Calliope modeling framework. Calliope is an open simulation tool for simulating energy systems and optimizing different energy carriers [22]. In general terms, the proposal is to determine the sizing of the systems that make up the electric power generation, electrolyzer (ELZ), and FC for a green $H_2$ facility necessary to provide a stable amount of electric energy of 1 $MWh_e$ (megawatt hour electric) and 0.10 $MWh_t$ (megawatt hour thermal) at all times.

According to the demand to be supplied, the study proposes two scenarios determined by the base indicator for PV generation (IBA.PV). This indicator (IB: $MWh/MW_{peak)}$ is valid to determine different sizes of photovoltaic plants in different scenarios from the total electric power generation per year based on 1 $MW_{peak}$. Furthermore, the months of highest (IBMax.PV) and lowest (IBMin.PV) generation allow estimating different plant configurations in the assessment to produce a 1 $MWh_e$.

- Scenario 1: Month with the minimum indicator of power generation from the photovoltaic system: IBMin.PV without and with electric and thermal storage.
- Scenario 2: Month with the maximum power generation indicator from the photovoltaic system: IBMax.PV without and with electric and thermal storage.

Various solutions have been determined to achieve 1 $MWh_e$ from an FC and compare it with the same energy produced from a Diesel Generator (DG). Also, power and heat were generated with the FC technologies. The use of FC as a Combined Heat and Power (CHP) technology has been worked on by other authors and allows for minimizing CAPEX by increasing the overall efficiency of the $H_2$ installation [23–25]. The data used in this study came from various sources [26,27] and are shown in Table 1.

*Table 1. Technical and economic input data for the port of study*

| PV System | | |
|---|---|---|
| **Parameter** | **Value** | **Unit** |
| Installed Capacity | 4 | MW |
| Loss factor | 14 | % |
| Investor Efficiency | 0.96 | - |
| Cost of Investment in PV plant | 750 | USD$/kW |

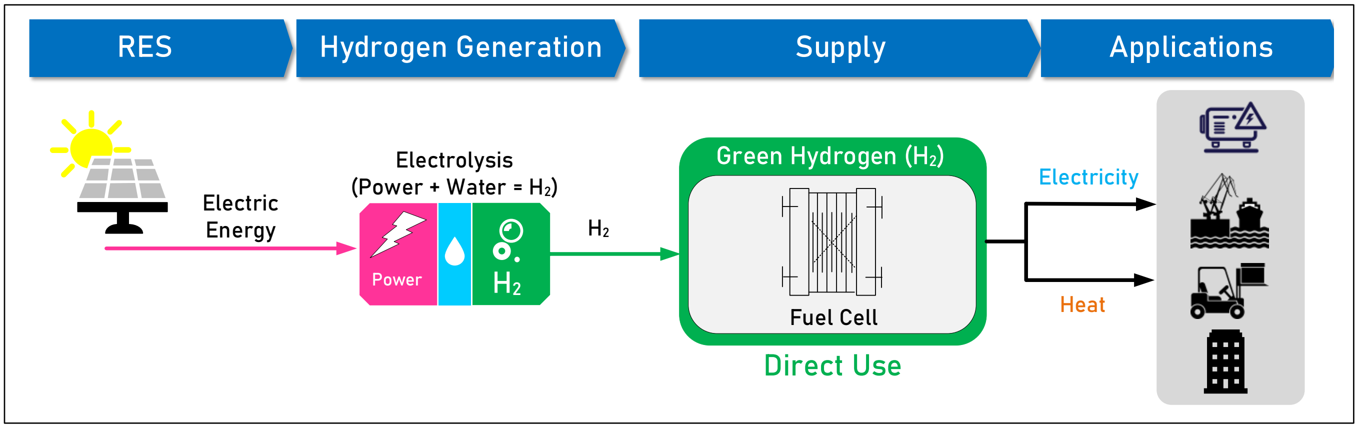

*Fig. 1 Scheme of a simplified value chain for the end-use of green $H_2$*

*Continuation Table 1.*

| **$H_2$ System** | | |
|---|---|---|
| **Parameter** | **Value** | **Unit** |
| Cost of O&M of ELZ and FC | 7.5 | USD\$/kW |
| Life Time for PV Plant | 25 | year |
| Fuel cell efficiency $(\eta_{FC} = \frac{E_{out,FC}}{E_{in,FC}})$ | 0.50 | - |
| Electrolyzer efficiency $(\eta_{ELZ} = \frac{E_{out,ELZ}}{E_{in,ELZ}})$ | 0.65 | - |
| Lower Heating Value of $H_2$ $(LHV_{H2})$ | 33.3 | $kWh/kg_{H2}$ |
| Cost of Investment for ELZ and FC | 1600 | USD\$/kW |
| Cost of O&M for ELZ and FC | 80 | USD\$/kW |
| ELZ: $H_2$ production in LT | 750,075 | $kg_{H2}$ |
| FC: Electric Power Production in LT | 12,500 | MWh |
| Prorate FC | 16 | USD\$/MWh |
| Prorate ELZ | 0.82 | USD\$/$kg_{H2}$ |
| Prorate $ELZ_{eq}$ = (Prorate ELZ/$LHV_{H2}$) | 0.02 | USD\$/$kWh_{eq,H2}$ |

*Continuation Table 1.*

| **DG System** | | |
|---|---|---|
| **Parameter** | **Value** | **Unit** |
| Prorate PV (June) | 18.93 | USD\$/MWh |
| Hours of Operation per day for ELZ and FC | 8 | h |
| Efficiency $(\eta_{DG} = \frac{E_{out,DG}}{E_{in,DG}})$ | 0.38 | - |
| Diesel Density | 846 | $kg/m^3$ |
| Higher Heating Value of Diesel $(HHV_D)$ | 12.67 | $kWh/kg_D$ |
| Cost of Diesel | 1 | USD\$/litter |

## 3. RESULTS AND DISCUSSION

The authors [28] have identified the conventional energy-consuming equipment that can be replaced by energy from $H_2$, mainly the mobility and static applications. It is known that not all ports have the same purpose and energy consumers. Nevertheless, the results in proposing a value chain for the end-use of green $H_2$ in similar facilities are replicable despite these differences and scalable in many cases.

As a result of the evaluation to meet the demand of 1 $MWh_e$ and 0.10 $MWh_t$, Figure 2 shows the study port's electric and thermal demand curves. The electrical demand is satisfied for scenario 2 of maximum availability of daily PV energy. However, in scenario 1 the FC cannot supply the demanded electrical energy. Therefore, in scenario 1 a part of the electrical energy is supplied for the grid. In both scenarios, the energy generated is not stored because PV energy is highly available. The thermal demand in Figure 3 shows that there is always an excess for both scenarios. In this case, including storage, this energy could be delivered as district heating energy. In addition, the annualized base indicator (IBA.PV) for the scenarios was:

- Scenario 1: IBMin.PV = 2.67 $MWh/MW_{peak}$;
- Scenario 2: IBMax.PV = 5.60 $MWh/MW_{peak}$;

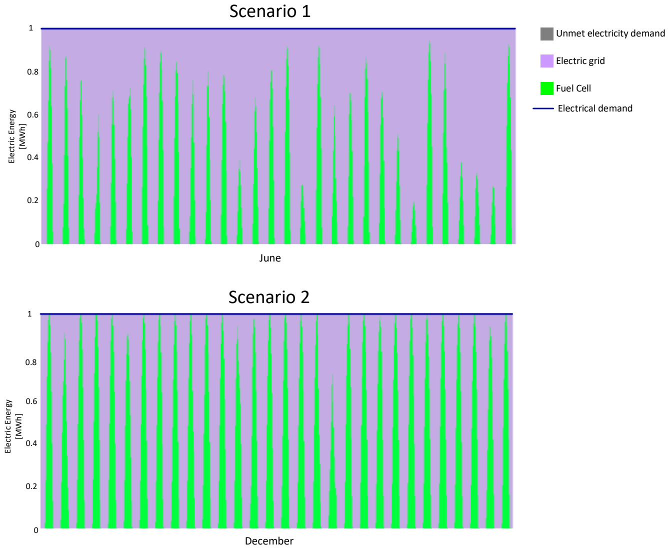

*Fig. 2 Electric energy generated in both scenarios*

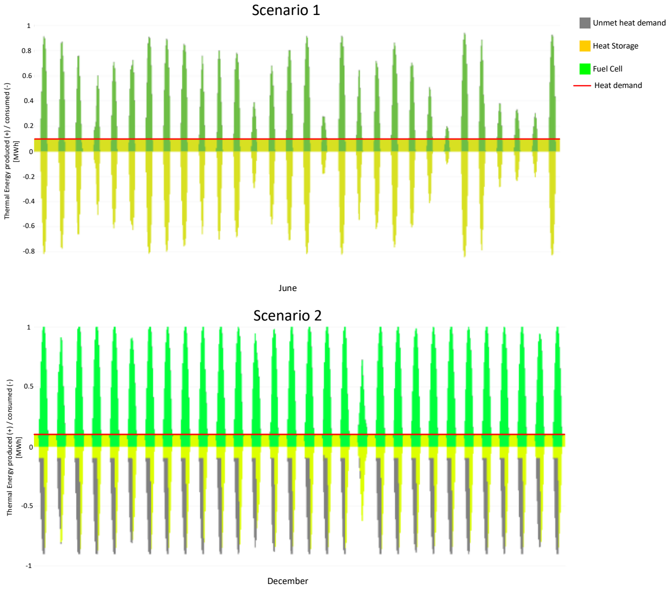

*Fig. 3 Thermal energy generated in both scenarios with the storage*

Therefore, to generate 1 $MWh_e$ have used the equations raised by [29], the FC input is required the quantity of 60 $kg_{H2}$. The electrical energy that was supplied to the electrolyzer was 3.1 $MWh_e$. Based on these results, the two scenarios were determined that the photovoltaic plant produces the minimum energy necessary to generate 3.1 $MWh_e$ in one day of operation.

The price of energy parity (USD\$/$MWh_e$) produced by the DG and FC was determined for 1 L of diesel equal to 1 USD\$. Then, the cost of generating 1 $MWh_e$ of energy using FC is determined to be USD\$245. As the quantity of green $H_2$ required is 60 $kg_{H2}$ to generate 1 $MWh_e$, the cost of 1 $kg_{H2}$ was up 4.1 times higher than the cost of 1 L of diesel. Therefore, the different scenarios and the calculated data, the respective green $H_2$ production was:

*Table 2. Green $H_2$ generated for the different scenarios*

| **Scenarios** | **Power from the PV Plant [$MW_{peak}$]** | **June [$kg_{H2}$/day]** | **December [$kg_{H2}$/day]** |
|---|---|---|---|
| (1) | 1.15 | 60 | 126 |
| (2) | 0.55 | 29 | 60 |

### *3.1 Levelized Cost of Energy*

The operation parameters and costs associated with green hydrogen value chain technologies were estimated based on the *LCOE*. Assumptions of operation and system costs were made according to [13,30]. Therefore, according to the data shown in Table 1, the *LCOE* calculation in Calliope was performed in Figure 4.

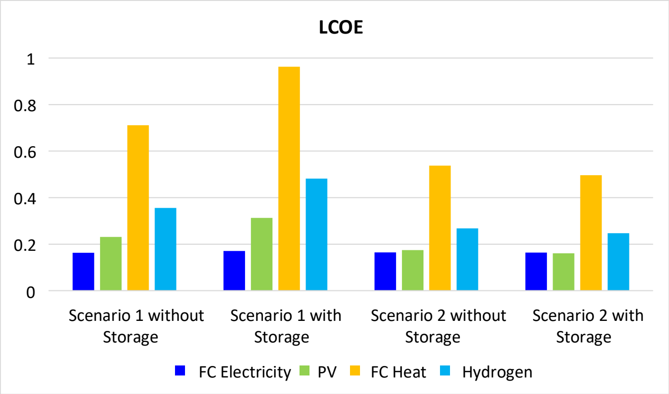

*Fig. 4 LCOE for the scenarios stuied*

Finally, Figure 5 represents a referential scheme of the proposed complete value chain for a final supply of the electric and heat demand (the position of these systems in the figure is representative).

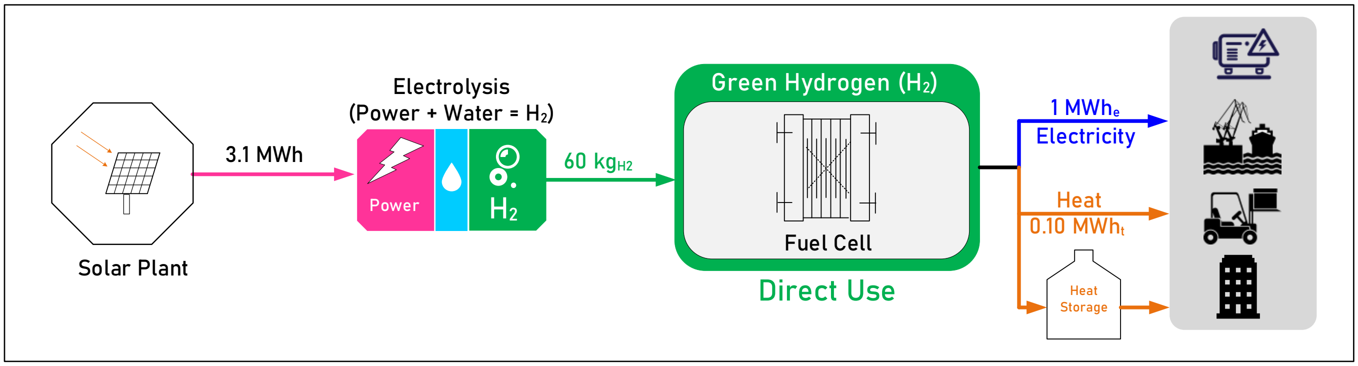

*Fig. 5 Final chain value for green $H_2$ used in the port application*

## 4. CONCLUSIONS

The work presents a value chain for green $H_2$ in a port installation that includes electricity generation using photovoltaic solar energy, electrolyzers for $H_2$ production, and fuel cells to generate the electricity required. Studying determined potential green $H_2$ consumers, most analyzed have a diesel fuel consumption. Therefore, the system must supply approximately 60 $kg_{H2}$ in the fuel cell with a 50% electrical and heat demand efficiency. This requirement was covered by a 65% efficient electrolyzer whose energy consumption is 3.1 $MWh_e$, which a photovoltaic solar plant supplied.

In both scenarios, thermal energy can be stored for later use. As for the electrical energy in scenario 1, there must always be a supply from the electrical network. The scenario 2, grid power is only needed when no PV power is available. The photovoltaic plant was sized in both scenarios, the month with the minimum power generation (June) of 2.67 $MWh/MW_{peak}$ and the month with the maximum generation (December) of 5.60 $MWh/MW_{peak}$.

With the parity of the energy price produced by the diesel generator and the fuel cell, it was obtained that the cost of 1 $kg_{H2}$ could be up to 4.1 times higher than the cost of 1 L of diesel. The Levelized Cost of Energy for green $H_2$ shows that scenario 2 has lower values for all carries than scenario 1. This study shows that in the short term, part of the green $H_2$ produced in-situ using photovoltaic solar energy could be implemented in port applications through a complete value chain.

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