SolarPACES 2022, 28th International Conference on Concentrating Solar Power and Chemical Energy Systems

Analysis and Simulation of CSP and Hybridized Systems

https://doi.org/10.52825/solarpaces.v1i.669

Published: 20 Dec. 2023

Techno-Economic Analysis of the Integration of Large-Scale Hydrogen Production and a Hybrid CSP+PV Plant in Northern Chile

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Abstract. Green hydrogen has been considered as one of the energy carriers of the future, and Chile can become a production leader due to its great renewable energy potential. Cheap electricity is one of the key drivers for making green hydrogen a cost-effective energy carrier for many sectors. However, without energy storage, only a small operational electrolysis capacity can be achieved, and therefore, the share of the CAPEX in the levelized cost of hydrogen ($LCOH_2$) increases [1]. This work set out to conduct a techno-economic analysis for the integration of large-scale green hydrogen production and a hybrid CSP+PV plant of 100 MW_e in northern Chile, one of the world's solar hotspots. For a better understanding on the benefits of such integration, the performance of the hybrid solar plant was compared to the performance offered by each independent solar technology and with a grid-connection via a PPA mechanism. In addition, this study takes into account the costs of storage and transport to potential local and international consumers.

Keywords: Hybrid CSP+PV plant, Photovoltaic Energy (PV), Concentrated Solar Power (CSP), Green Hydrogen, Electrolyzers, Levelized Cost of Hydrogen ($LCOH_2$)

1. Introduction

In the face of climate change and on the basis of the Paris Agreement, in June 2019, the Chilean government announced Chile's commitment to achieve carbon neutrality by 2050, i.e., that the country reaches a state of balance between emissions and absorptions of greenhouse gases, mainly carbon dioxide (CO_2). To achieve this ambitious goal, one of the great allies that has gained strength recently is green hydrogen, i.e., hydrogen generated by renewable energy sources without polluting emissions. Although there are several renewable energy-based solutions for producing hydrogen, currently the most established option for producing green hydrogen is the electrolysis of water powered by renewable electricity.

While green hydrogen has begun to gain prominence, one of the main barriers that limits its use on a large-scale is the cost of the energy required for its production. As a consequence of the latter, Chile has been identified as one of the most competitive countries for the development and production of green hydrogen due to the enormous potential for generating electricity from renewable resources, particularly solar energy. To take advantage of this solar resource, there are two main types of solar energy technologies: Photovoltaics (PV) and Concentrated Solar Power (CSP). On the one hand, PV systems are the most economical and widespread solar electric technology in the world. However, electrical storage in PV is currently not economically feasible, so its production is intermittent and limited by daily and seasonal fluctuations. The latter makes it difficult to guarantee a year-round baseload production that can be used for large-scale green hydrogen production. On the other hand, CSP technology integrated with Thermal Energy Storage system (TES) represents a suitable option to improve the dispatch capacity and the capacity factor; however, it has a much higher cost mainly due to the field and storage components necessary to ensure a continuous and reliable generation of electricity. To solve the limitations of each technology, the concept of hybrid CSP + PV plant has been studied by different authors in recent years seeking to exploit the main advantages of each solar technologies in an optimal manner and a single application. Previous studies in the area have focused on the assessment of hybrid solar plants for electricity generation in particular or integrated to the production of fresh water [2], cooling or process heat [3]. However, very little is currently known about hybrid CSP + PV plants dedicated to green hydrogen production in the world, and to date there are no Chile-based studies on the subject.

2. Methodology

2.1 Simulation Tool

The analysis of the different pathways was conducted by means of a simulation tool created for this work, which was based on PySAM [4], an open-source python-based programming interface that provides access to all capabilities of the National Renewable Energy Laboratory's System Advisor Model (SAM), but which also allows developers to implement and integrate custom scenarios of novel technologies that are not yet built into SAM. In this work, PySAM was used to build a computational code to achieve an operational strategy that allows an optimal interplay between PV, CSP and hydrogen production as a whole.

2.2 Location and Resource

The annual performance of the plants was determined by simulation models considering a meteorological database of hourly resolution in the vicinity of the city of Antofagasta. The Atacama Desert, in northern Chile, is the driest place on the planet and has the highest solar radiation in the world. Additionally, this place presents the best conditions in terms of atmospheric attenuation [5], which is very attractive for the solar industry in general and, particularly, for solar power concentration (CSP), where Direct Normal Irradiance (DNI) is key and reaches values greater than 3000 kWh/m^2 per year [5].

2.3. Analyzed Scenarios

2.3.1 Case 1: Stand-Alone PV

This case considers a direct coupling of an electrolyzer to a solar PV system in order to produce green hydrogen.The PV plant was generated and simulated through the "Pvwattsv8" module of PYSAM, which allows the creation of a PV project using a few basic inputs.

2.3.2 Case 2: Stand-Alone CSP

This case considers a direct coupling of an electrolyzer to a CSP system for hydrogen production. A central receiver system coupled with molten-salt storage technology was chosen as the CSP technology, as it allows higher operating temperatures than those achievable by a parabolic trough plant, and therefore, better power cycle efficiencies. This system was generated and simulated using the PySAM module "TcsmoltenSalt".

2.3.3 Case 3: Hybrid CSP+PV

The hybrid CSP+PV system combines both PV and CSP subsystems for green hydrogen production. To simulate this case, independent PV and CSP models were linked to achieve a synergistic operation that provides a base load capacity of 100 MW_e as a whole. In the operation strategy, PV has the priority of feeding over CSP, that is, when the PV plant is producing electricity, the CSP plant reduces or ceases its production, storing the residual heat from the receiver in the TES to be used in hours of low or no solar radiation.

2.4 Technical Analysis

2.4.1 Load Factor

To explore and demonstrate the benefits of hydrogen production from the combination of PV and CSP technologies, the load factor of the electrolyzer was used as one of the main performance metrics, i.e., the ratio of its total to the maximum possible utilization.

2.4.2 Hydrogen Production

The amount of hydrogen produced was estimated using the following equation [6]:

$$m_{H_2} = \frac{\eta_{el} E_{el}}{LHV_{H_2}} \tag{1}$$

where LHV_{H2} is the lower heating value of hydrogen, equal to 33,33 (kWh/kgH_2), E_{el} is the electrical energy input (kWh) and η_{el} is the electrolyzer's efficiency.

2.4.3 CO_2 Emission Reduction Potential

The environmental benefit of the analyzed solar plants was established taking into account the abatement of CO_2 emissions. This metric was calculated according to the following equation:

$$tCO_2\left(\frac{tCO_2\,eq}{year}\right) = EF\left(\frac{tCO_2\,eq}{MWh}\right) \cdot E\left(\frac{MWh}{year}\right) \tag{2}$$

where tCO_2 represents the CO_2 savings from the operation of a solar power project, EF is the emission factor and E represents the amount of electricity generated by the plant. The emission factor used was 0,3834 tCO_2 equivalent per MWh generated. This value corresponds to the average annual emissions factor of the National Electricity System (SEN) reported by the National Energy Commission [7].

2.5 Economic Analysis

2.5.1 Levelized Cost of Energy (LCOE)

The simple levelized cost of energy is calculated using the following formula [8]:

$$LCOE = \frac{\sum_{t=0}^{N} \frac{CAPEX_t}{(1+i)^t} + \sum_{i=1}^{N} \frac{OPEX_t}{(1+i)^t}}{\sum_{t=1}^{N} \frac{E_t(1-d)^t}{(1+i)^t}} \tag{3}$$

where $CAPEX_t$ is the capital expenditures in the year t, $OPEX_t$ is the operations and maintenance expenditures in the year t, E_t is the electricity generation in the year t, i is the discount rate, d is the annual degradation factor and N is the useful economic life of the system. CAPEX (capital expenditure) represents all capital or investment expenses that a company must incur in.

Tables 1 and 2 details the installation and operation costs of the off-grid CSP and PV systems for hydrogen production. For the current scenario (2021), SAM default values were adopted, and for the future scenario (2030) the prices were set according to the energy price offered in the Chilean electricity tender in August 2021.

Table 1. Cost distribution for economic evaluation of the 100 MW_e CSP power plants [9][10].

Element	CAPEX 2021	CAPEX 2030	Cost Reduction
Site preparation	16 (USD/m^2)	10 (USD/m^2)	35,5%
Solar field	140 (USD/m^2)	50 (USD/m^2)	59%
Tower cost fixed	3000000	2,189,781	27%
Receiver reference cost	103000000	75182481,75	27%
TES	22.00 (USD/kWh$_t$)	10.00 (USD/kWh$_t$)	54,5%
Power block	1330 (USD/kW)	700 (USD/kW)	47,4%
Contingencies	5%	2%	

Table 2. Cost distribution for economic evaluation of the 100 MW_e PV power plant.

Element	CAPEX 2021 (USD/Wdc)	CAPEX 2030 (USD/Wdc)	Cost Reduction
Module	0,41	0,17	58,5%
Land preparation	0,02	0,01	50%
Balance of system	0,20	0,10	50%
Installation labor	0,11	0,11	0%
Contingency	1%	1%	

2.5.2 Combined LCOE

The weighted average of the PV and the CSP plant's LCOE is calculated using the following equation [8]:

$$LCOE_{hybrid} = \frac{LCOE_{PV} \cdot E_{PV} + LCOE_{CSP} \cdot E_{CSP}}{E_{PV} + E_{CSP}} \tag{4}$$

where $LCOE_{CSP}$ and $LCOE_{PV}$ represents the levelized cost of electricity of the CSP and PV plants respectively, and E_{CSP}, E_{PV} refers to the annual energy generation of the CSP and PV plants respectively.

2.5.3 Levelized Cost of Hydrogen ($LCOH_2$)

The model is based on a straightforward calculation in which the various system costs are evaluated, and the sum is divided by the amount of hydrogen produced. According to the definition provided by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) [11], the $LCOH_2$ can be mathematically defined as:

$$LCOH_2 = P_{inst} \cdot CAPEX \cdot \frac{CRF + OPEX}{h \cdot f_p \cdot Q_{H_2}} + Q_{H_2O} \cdot P_{H_2O} + Q_e \cdot P_e - Q_{O_2} \cdot P_{O_2} \tag{5}$$

where P_{inst} is the installed capacity of the electrolyzer, CAPEX is the investment cost according to installed capacity; CRF is the capital recovery factor, f_p is the plant factor; OPEX is the maintenance costs function, defined as a percentage of the investment; h is the number of hours in a year; Q_{H2} is the hydrogen production capacity [kgH_2/h]; Q_{H2O} is the amount of water consumed [m^3/kgH_2]; P_{H2O} is the water price [USD/m^3]; Q_e is the amount of electricity consumed [kWh/kgH_2] and P_e=LCOE is the electricity price [USD/kWh].

Table 3. Electrolyzer capital costs [12].

Element	CAPEX 2021	CAPEX 2030	Cost Reduction
PEM Electrolyzer	1100 (USD/kW)	650 (USD/kW)	41%
Alkaline Electrolyzer	500 (USD/kW)	400 (USD/kW)	20%

2.5.4 Indirect on-grid connection to the electrolyzer: PPA mechanism

For the off-site or virtual PPA alternative, i.e., assuming that electricity is purchased from a solar supplier, the following base costs and plant factors were assumed: These prices were estimated from the energy bids of solar generators in the 2017 and 2021 tenders, and do not consider costs related to power, transmission and distribution of energy. An approximate cost of USD 24,77 must be added to obtain the total cost of electricity, as indicated in [11].

2.5.5 Hydrogen Conditioning and Storage Costs

The two current state of the art methods for hydrogen storage technologies, liquefied and compressed, were considered. For each of these methods, a conversion or conditioning module (compressor and liquefaction unit) and a storage module (storage tanks) were taken into account, according to the techno-economic parameters reported by [6] and [13].

2.5.6 Estimation of Transportation Costs

Hydrogen is assumed to be transported for short distances via pipeline or trucks (to the port of Mejillones and to a mining company, 106 km and 85 km away from the electrolysis plant, respectively) and to Germany by ship (port of Hamburg, approximately 17405 km from the port of Mejillones). Transport costs are scaled linearly as a function of distance derived from IEA [14] [12].

3. Results and discussion

3.1 Economic Results

Table 4. Minimum LCOE values achieved.

Configuration/Scenario	Standard cost scenario (2021)	Outlook scenario (2030)
LCOE PV (USD/MWh)	30,61	14,23
LCOE CSP (USD/MWh)	69,78	35,43
LCOE Hybrid (USD/MWh)	65,84	33,42

From Table 4 it can be seen that in both the current and future scenarios, PV technology achieves the lowest specific cost of energy with a reduction of 54% between both time scenarios, mainly due to its low investment costs.

Table 5. Minimum $LCOH_2$ values achieved (USD/kgH_2).

Configuration/Scenario	ALK - 2021	PEM - 2021	ALK - 2030	PEM – 2030
$LCOH_2$ PV	2,38 – 2,65	4,05 – 4,34	1,39 – 1,52	1,92 – 2,07
$LCOH_2$ CSP	3,81 – 4,23	5,10 – 5,46	2,02 – 2,19	2,32 – 2,50
$LCOH_2$ Hybrid	3,59 – 3,99	4,81 – 5,16	1,91 – 2,07	2,20 – 2,36

Table 5 confirms that from a purely economic point of view, green hydrogen production based on stand-alone PV reaches the lowest hydrogen production costs due to its low CAPEX, which is mainly attributed to the rise of China's solar PV industry. Next, in ascending order of cost, are hybrid plants and, lastly, hydrogen production based on stand-alone CSP. The costs achieved for the current scenario are not the same for all pathways analyzed; however, they are clearly not competitive with fuel-based or “grey” hydrogen today, regardless of the case under analysis. For the next decade, this situation is projected to change, as PV-based generation (PEM and alkaline) and hybrid plant generation (alkaline) could reach, under certain favorable conditions, the range of competitive values, below 2 USD/kgH_2 (fossil fuel range, its main competitor in the market).

$LCOH_2$ in the current scenario for PV-ALK is consistent with the cost reported by the IEA for Chile in the Global Hydrogen Review 2021 [14]. Overall, all costs found for 2021 are also in accordance with the levelized cost of hydrogen based on renewable energies as reported by the IEA in its report The Future of Hydrogen, which fluctuates between 3 and 7,5 USD/kgH_2 [12]. In addition, the hydrogen production cost estimates for the next decade are in general accord with recent studies indicating that by 2030, renewable hydrogen's cost will range from ~USD1,3 – 3,5/kgH_2 (broader range). These sources include Bloomberg New Energy Finance (BNEF), International Renewable Energy Agency (IRENA), International Energy Agency (IEA) and the Hydrogen Council (H_2 Council).

Table 6. $LCOH_2$ supplied through a PPA mechanism (USD/kgH_2) - ALK electrolyzer.

Configuration/Scenario	Standard cost scenario (2021)	Outlook scenario (2030)
$LCOH_2$ - PPA (PV based)	3,66	2,56
$LCOH_2$ - PPA (CSP based)	4,96	3,36

Although an off-site PPA mechanism stabilizes the hydrogen production, the additional transmission charges make the cost of energy higher than a direct connection, making hydrogen production between 35% and 68% more expensive, depending on the solar technology. Additionally, an off-site solar PPA contract does not ensure today that the energy consumed at the hydrogen production site is actually 100% renewable and therefore that the hydrogen is effectively green.

Table 7. Levelized cost of hydrogen storage (USD/kgH_2) - ALK electrolyzer (2021).

Configuration/Scenario	Compressed H_2 (GH_2)	Liquid H_2 (LH_2)
PV	0.37	3.03
CSP	0.24	1.14
Hybrid	0.23	1.09

The lowest specific or unit cost of storage is achieved with a hybrid solar plant that stores hydrogen as a high-pressure gas (0,23 USD/kg$_{H2}$). The latter is explained by the higher utilization of the electrolyzer, and therefore, the higher amortization of the investment in conditioning units and storage tanks for each kg of hydrogen produced.

Table 8. Estimated transport costs per unit of hydrogen (USD/kgH_2).

Destination	Truck (Gas H_2)	Truck (LH_2)	Pipe	Ship
Port of Mejillones	0,75	1,25	0,25	-
Port of Hamburg	0,75	1,25	0,25	3,9
Mining Company	0,70	1,20	0,20	-

For short distances, compressed hydrogen gas appears to be the cheapest option, particularly in the case of pipelines (although this option implies the construction of new gas pipelines), followed by compressed gas trucks. However, since the last two options increase considerably in cost with remoteness, for long distances, the preferred option for hydrogen supply is by ship. It should be noted that the cost of transporting hydrogen to the port of Hamburg from the electrolysis plant is a combination of pipeline and ship. Finally, it should be pointed out that Hamburg's port is projected to be one of the main supply centers for hydrogen in Europe, and Chile already has a Memorandum of Understanding on export-import of green H_2 with this port.

3.2 Technical Results

As shown in Figure 1, although stand-alone PV-based hydrogen production is the cheapest alternative, it may not provide the necessary volumes for some demand cases, like e-fuel or ammonia production (around 218% less annual production than a hybrid solar plant). In contrast, a hybrid solar plant can produce not only greater amounts of electricity and hydrogen, but also avoid the emission of about 220 $ktCO_2$ more than a stand-alone PV plant per year, making it also a better environmental option.

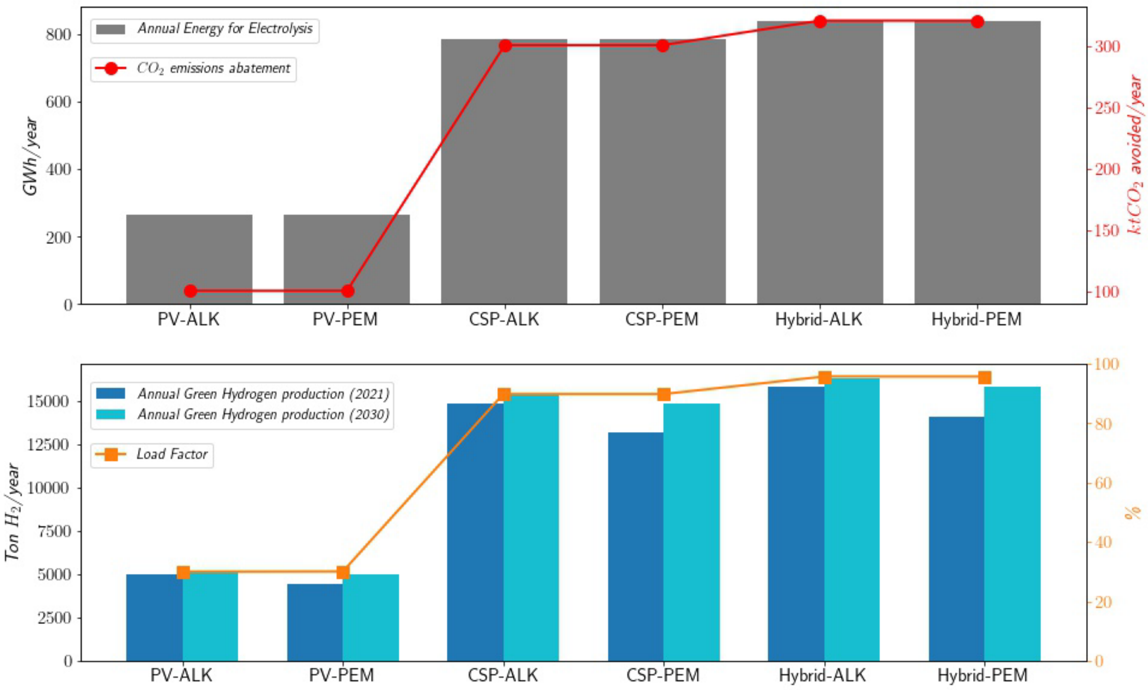

Figure 1. Performance comparison of the different pathways.

4. Conclusions

The main conclusions of this work are as follows: First, from an economic point of view, this work has identified that none of the solar hydrogen production pathways achieve costs lower than 2 (USD/kgH_2) in the current scenario (2021). This situation would change in the next decade (2030), when green hydrogen generation directly coupled to stand-alone PV would reach the lowest specific cost among the analyzed pathways (1,39 USD/kgH_2). Furthermore, given certain favorable conditions, green hydrogen produced from hybrid solar plants and an alkaline electrolyzer could reach a cost of 1,90 USD/kgH_2, i.e., within the range of fossil-fuel based hydrogen, its closest competitor. Second, from a technical point of view, a hybrid solar plant offers complementary or added benefits such as greater stability and reliability for hydrogen production, as it is more flexible and less dependent on daily and seasonal variation of the solar resource. Third, this work has shown that the ranking order of economic merit obtained in production changes when the specific cost of storing daily hydrogen production is analyzed. Moreover, the results of this study support the idea that a direct connection or coupling between an electrolyzer and a renewable generation plant is more cost-effective than an indirect connection via a PPA mechanism. In conclusion, if each pathway is analyzed holistically, the hybridization of solar technologies would not only be feasible, but also imperative to achieve a balance between a competitive price (not necessarily the lowest) and greater potential for large-scale solar hydrogen production and its derivatives (vast amounts of production) compared to stand-alone technologies with comparable power rating in 2030.

Data availability statement

The data that support the findings of this study are available from the corresponding author, Francisco Moraga, upon reasonable request.

Author contributions

Francisco Moraga: Conceptualization, Data curation, Investigation, Methodology, Software, Validation, Writing – original draft. **María Teresa Cerda:** Conceptualization, Supervision, Writing – review & editing. **Frank Dinter:** Supervision, Writing – review & editing. **Francisco Fuentes:** Supervision, Writing – review & editing.

Competing interests

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.

References

1. A. Rosenstiel, N. Monnerie, J. Dersch, M. Roeb, R. Pitz-paal, and C. Sattler, "Electrochemical hydrogen production powered by pv/csp hybrid power plants: A modelling approach for cost optimal system design," Energies, vol. 14, no. 12, 2021, doi: https://doi.org/10.3390/en14123437.
2. C. Mata-Torres, R. A. Escobar, and J. M. Cardemil, "Techno-economic analysis of CSP+PV+MED plant: Electricity and water production for mining industry in Northern Chile," AIP Conf. Proc., vol. 2033, November, 2018, doi: 10.1063/1.5067179.
3. J. M. Cardemil, A. R. Starke, A. Zurita, C. Mata-Torres, and R. Escobar, "Integration schemes for hybrid and polygeneration concentrated solar power plants," Wiley Interdiscip. Rev. Energy Environ., vol. 10, no. 6, pp. 1–22, 2021, doi: https://doi.org/10.1002/wene.412.
4. "NREL-PySAM — NREL-PySAM 2.2.4 documentation." https://nrel-pysam.readthedocs.io/en/master/ (accessed Oct. 17, 2021).
5. A. Marzo et al., "Solar extinction map in Chile for applications in solar power tower plants, comparison with other places from sunbelt and impact on LCOE," Renew. Energy, vol. 170, no. October 2015, pp. 197–211, 2021, doi: https://doi.org/10.1016/j.renene.2021.01.126.
6. F. I. Gallardo, A. Monforti Ferrario, M. Lamagna, E. Bocci, D. Astiaso Garcia, and T. E. Baeza-Jeria, "A Techno-Economic Analysis of solar hydrogen production by electrolysis in the north of Chile and the case of exportation from Atacama Desert to Japan," Int. J. Hydrogen Energy, vol. 46, no. 26, pp. 13709–13728, 2020, doi: https://doi.org/10.1016/j.ijhydene.2020.07.050.
7. "Factores de Emisión – Energía Abierta | Comisión Nacional de Energía." http://energiaabierta.cl/visualizaciones/factor-de-emision-sic-sing/ (accessed Oct. 17, 2021).
8. L. Bousselamti and M. Cherkaoui, "Modelling and Assessing the Performance of Hybrid PV-CSP Plants in Morocco: A Parametric Study," Int. J. Photoenergy, vol. 2019, 2019, doi: https://doi.org/10.1155/2019/5783927.
9. "Home - System Advisor Model (SAM)." https://sam.nrel.gov/
10. "2030 Solar Cost Targets | Department of Energy." https://www.energy.gov/eere/solar/articles/2030-solar-cost-targets (accessed Jun. 01, 2023).
11. D. G. für I. Z. (GIZ) G. Rodrigo Vásquez, Felipe Salinas, "Tecnologías del Hidrógeno y perspectivas para Chile," p. 135, 2018.
12. "The Future of Hydrogen," The Future of Hydrogen, June, 2019, doi: https://doi.org/10.1787/1e0514c4-en.
13. M. Reuß, T. Grube, M. Robinius, P. Preuster, P. Wasserscheid, and D. Stolten, "Seasonal storage and alternative carriers: A flexible hydrogen supply chain model," Appl Energy, vol. 200, pp. 290–302, 2017, doi: https://doi.org/10.1016/j.apenergy.2017.05.050.
14. "Global Hydrogen Review 2021," Global Hydrogen Review 2021, 2021, doi: https://doi.org/10.1787/39351842-en.