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THE ENVIRONMENTAL IMPACT OF HYDROGEN PRODUCTION AND EXPORTATION WITHIN THE FRAMEWORK OF THE CHILEAN GREEN HYDROGEN STRATEGY.

TESIS PARA OPTAR AL GRADO DE MAGÍSTER EN CIENCIAS DE LA INGENIERÍA, MENCIÓN QUÍMICA.

MEMORIA PARA OPTAR AL TÍTULO DE INGENIERA CIVIL QUÍMICA

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RESUMEN DE LA TESIS PARA OPTAR AL GRADO DE:
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IMPACTO AMBIENTAL DE LA PRODUCCIÓN Y EXPORTACIÓN DE HIDRÓGENO EN EL MARCO DE LA ESTRATEGIA CHILENA DE HIDRÓGENO VERDE.

La producción de hidrógeno está adquiriendo cada vez más importancia en todo el mundo debido a la creciente atención a los sistemas de energía limpia y sostenible. Dado que el hidrógeno verde no emite dióxido de carbono durante la fase de uso, es un vector energético deseable y muchos países se han comprometido a adoptar estrategias nacionales para producir hidrógeno verde, siendo Chile uno de ellos. En este contexto, es importante abordar la pregunta de cuál ruta de producción de hidrógeno es la con el menor impacto ambiental.

Este estudio compara cuatro procesos de producción de hidrógeno mediante un análisis de ciclo de vida (ACV), considerando diferentes fuentes de energía renovable y estados del producto final (hidrógeno). Estos procesos incluyen la generación de hidrógeno basada en energía solar con compresión, la generación de hidrógeno basada en energía eólica con compresión, la generación de hidrógeno basada en energía solar con licuefacción y la generación de hidrógeno basada en energía eólica con licuefacción. Se utiliza la metodología ReCiPe para evaluar el impacto ambiental, presentando resultados agregados y desagregados.

Los resultados sugieren que no hay una diferencia significativa entre la generación de hidrógeno comprimido a partir de energía solar y eólica, ni entre la generación de hidrógeno licuado a partir de energía solar y eólica. Sin embargo, se observaron diferencias significativas al comparar la compresión y la licuefacción dentro de cada fuente de energía. Después de analizar los hallazgos, se determinó que la producción de hidrógeno a partir de energía eólica combinada con licuefacción tiene los puntos ReCiPe más bajos (3 E+10 puntos) debido principalmente al elevado consumo de energía durante la etapa de licuefacción (2.963 E+11 [kWh]).

Este estudio pone de manifiesto que los métodos de producción de hidrógeno evaluados generan emisiones a lo largo de su ciclo de vida. Por consiguiente, dado el papel crucial de la Estrategia Nacional en la reducción de emisiones en Chile, es fundamental que esta estrategia abarque todo el ciclo del proceso, y no se limite únicamente a la fase de operación como se considera actualmente.

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Hydrogen production is becoming increasingly important around the world as a result of the growing attention to clean and sustainable energy systems. Since green hydrogen emits no carbon dioxide during the use phase, it is a desirable energy vector and many countries have committed to adopting national strategies to produce green hydrogen, Chile being one of them. In this context, it is important to address the question of which hydrogen production route has the lowest environmental impact.

This study compares four hydrogen production processes by life cycle analysis (LCA), considering different renewable energy sources and final product states (hydrogen). These processes include solar energy-based hydrogen generation with compression, wind energy-based hydrogen generation with compression, solar energy-based hydrogen generation with liquefaction, and wind energy-based hydrogen generation with liquefaction. The impact assessment is addressed using the ReCiPe methodology, presenting aggregated and disaggregated results.

The findings suggest that there is no significant difference between compressed hydrogen generation from solar and wind energy, nor between liquefied hydrogen generation from solar and wind power. However, significant differences were observed when comparing compression and liquefaction within each energy source. After analyzing the findings, it was determined that hydrogen production from wind energy combined with liquefaction has the lowest ReCiPe points (3 E+10 points), primarily due to high energy consumption during the liquefaction stage (2.963 E+11 [kWh]).

This study highlights that the evaluated methods of hydrogen production generate emissions throughout their life cycle. Therefore, given the crucial role of the National Strategy in reducing emissions in Chile, it is essential for this strategy to encompass the entire process cycle, not just the operational phase as is currently considered.

Para todos aquellos que un día creyeron en mi. Para mi familia, amigos y en especial para mi gata.

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I would like to express my sincere gratitude to the University for giving me the opportunity to be part of its student community. Over these years, I have gained a wealth of knowledge both academically and personally. Despite the challenges I have encountered along the way, every obstacle I have overcome has been a valuable lesson. In particular, I would like to thank all the professors who have shared their wisdom with me and dedicated their time to my development as an engineer.

I am also deeply grateful to those who believed in me and my potential. To my family and friends who have always stood by my side, I thank you from the bottom of my heart for your unwavering support and for listening to me when I needed it. I would also like to thank my cat, who has been my emotional support throughout this journey. Finally, I am grateful to all those who, although not present today, have been fundamental to my journey and have contributed to my personal growth.

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Introduction

The world's attention is turning to clean and sustainable energy systems as a result of the growing concern over global warming. The intensive burning of fossil fuels for the production of energy is the primary cause of the atmosphere's rising concentration of greenhouse gases [1]. Driven by rising living standards, global energy consumption is expected to grow steadily over the coming decades [2]. Finding safer, cleaner and more diversified sources of energy could be a successful strategy for reducing and eliminating greenhouse gas emissions and meeting the world's energy needs [3].

Among the potential alternative sources of energy, hydrogen is a promising fuel [4]. Hydrogen, the simplest of elements, comprises solely of one proton and one electron. Typically, it forms compounds by combining with other substances, as seen in water, where it exists as two parts hydrogen to one part oxygen. Renowned for its efficiency and renewability, hydrogen stands as the most abundant element on Earth. Additionally, it is non-toxic and has the potential to create numerous job opportunities in the future [5].

Hydrogen as a fuel is environmentally attractive because -when consumed- the only by-product of its oxidation is water. However, hydrogen has been signed as an energy carrier [6], in consequence, requires a production process coupled with an energy source. It´s important to note that these hydrogen processes have an environmental impact throughout their lifecycle, from initial construction to eventual decommissioning [6].

The environmental impact of hydrogen depends on how it is produced [7]. Lower-emission hydrogen production methods have led to different classifications of hydrogen, such as *blue* and *green* hydrogen. Blue hydrogen is derived from natural gas through a process that incorporates carbon capture and storage. On the other hand, green hydrogen is produced by electrolysis of water that is powered by electricity from renewable energy sources [8] (see Figure 1.1). The technology of water electrolysis transforms renewable electrical power into storable chemical energy, yielding high-purity hydrogen. In the realm of the hydrogen economy paradigm, green hydrogen stands out as the cleanest energy resource, boasting the highest gravimetric energy density -energy content per mass of a system- of approximately 142 $[\frac{MJ}{kg}]$ [9].

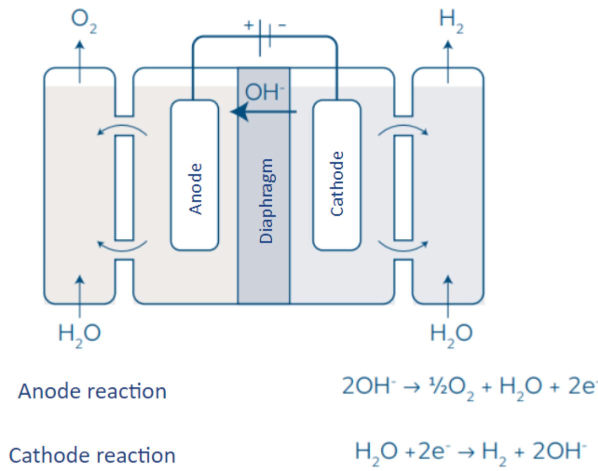


Figure 1.1: Water electrolysis diagram adapted from [10].

Worldwide demand for hydrogen has increased significantly, driven by the development of national hydrogen strategies and public and private sector investment in green hydrogen projects [11]. At the international conference *Chile 2020: Green Hydrogen Summit*, the Chilean strategy for the development of the country's green hydrogen industry was presented [12]. The strategy states that the country's ambition for 2030 is to be the world's leading producer of electrolysis-based green hydrogen. It aims to promote industrial development that is compatible with its environmental surroundings [13], showing a main focus on the operation of the industry.

On May 2, 2024, the Green Hydrogen Action Plan was unveiled. It is an important document that resulted from a participatory process involving over a thousand representatives from academia, civil society, the public, and corporate sectors. The plan outlines 81 measures organized into 18 lines of action to be implemented in two phases. The first phase (2023-2026) will focus on creating favorable conditions for industry development by establishing environmental, social, and labor standards, implementing an efficient permitting system, promoting scientific research, and advancing tax and financial incentives. The second phase (2026-2030) will concentrate on developing land-use planning instruments, regulations, local development, public participation, and human capital preparation for the realization of green hydrogen development [14].

Although hydrogen is generally considered a clean fuel when used, the production process may have negative environmental impacts [2], as measured by indicators such as global warming potential, ionizing radiation, ozone depletion potential, carcinogenic effects, photochemical ozone creation, freshwater & terrestrial acidification, particulate matter, freshwater eutrophication, among others. Studying at resource consumption, energy requirements and emissions from a life cycle perspective -looking at the sequence of events from the origin of a product to its final disposal- gives a complete picture of the environmental impact of hydrogen production [15]. Life cycle assessment (LCA) takes into account the life cycle perspective. LCA is widely used to support decision-making across a range of industries and policy areas [16].

Life cycle assessment has been applied to hydrogen production in different contexts in the past. Cetinkaya et al. [17] conduced a detailed LCA of five different methods of hydrogen production in their study. These methods include natural gas steam reforming, coal gasification, solar and wind-powered water electrolysis, and thermochemical water splitting with a Cu-Cl cycle. A case study was carried out specifically on a hydrogen fueling station located in Toronto, Canada, as well as the hydrogen resources in the vicinity. The lowest carbon dioxide equivalent (CO_2eq) emissions were found in thermochemical water splitting using the Cu–Cl cycle, which was followed by solar and wind electrolysis. However, compared to the systems based on renewable energy, conventional technologies like natural gas steam reforming, coal gasification, and thermochemical water splitting with the Cu–Cl cycle shown higher capacity for producing hydrogen.

Burmistrz et al. [18] thoroughly examined the particular advantages of the coal gasification hydrogen production process and compared the effects of the Shell and Texaco/GE technologies using the concept of life cycle assessment. The results suggest that using carbon capture equipment in coal gasification for hydrogen production can significantly reduce carbon footprint and improve the system's environmental benefits.

Romagnoli et al. study [19] serves as a foundation for a quantitative life cycle assessment method that evaluates the environmental effects of a photobiological hydrogen generation process that is scaled up. The analysis's findings demonstrate that producing energy with biohydrogen offers more environmental benefits than using a source that depends on fossil fuels in terms of avoided carbon dioxide (CO_2) emissions. By using forced sulfur deprivation in conjunction with cycle photobiological hydrogen generation from green algae (*C. reinhardtii*), the analysis quantified the averted CO_2 emissions from fossil fuel.

Valente et al. [20] employs harmonised life-cycle indicators to investigate hydrogen's impact on the environmental performance of hydrogen cars with proton exchange membrane fuel cells (PEMFC). The study focuses on three hydrogen fuel options: (i) renewable hydrogen from biomass gasification; (ii) renewable hydrogen from wind-power-based electrolysis; and (iii) traditional, fossil-based hydrogen from steam methane reforming. The study highlights that the choice of hydrogen fuel significantly affects the life-cycle performance of PEMFC vehicles when assessed from a well-to-wheels perspective. To decrease carbon and energy footprints, renewable hydrogen must be used instead of conventional hydrogen manufactured through steam methane reforming.

The study conducted by Reiter et al. [21] presents a life cycle assessment of power-to-gas technology. The research examines the significant parameters that impact primary energy demand and global warming potential (GWP) while producing hydrogen or methane in power-to-gas systems. The study includes the complete production process of hydrogen and methane, from cradle to gate. The results of the research suggest that the environmental sustainability of hydrogen and methane produced through power-to-gas technology significantly relies on the source of electricity generation. Using renewable energy sources such as wind power or photovoltaics to produce hydrogen and methane through power-to-gas technology has the potential to reduce GWP and primary energy demand.

Gerloff [22] conducted a study that examines the environmental impact of green hydrogen production, focusing on three electrolysis technologies: alkaline electrolysis (AEC), polymer electrolyte membrane electrolysis cell (PEMEC), and solid oxide electrolysis cell (SOEC). This paper considers different energy scenarios for Germany (2019, 2030, 2050, and Renewable Energy), with increasing wind and solar energy shares. The results show decreasing CO_2 emissions with higher renewable energy shares, particularly with solid oxide electrolysis. Comparisons with conventional hydrogen production and conventional alternatives reveal the superiority of renewable energy scenarios in reducing CO_2 emissions. Additionally, SOEC demonstrates the lowest environmental impact across various energy scenarios, taking into account the indicators of global warming potential, ionizing radiation, ozone depletion potential, carcinogenic effects, photochemical ozone creation, freshwater & terrestrial acidification, particulate matter and freshwater eutrophication.

The research of Dufour et al. [23] evaluates emerging hydrogen production methods using life cycle assessment, comparing them to conventional processes. Water photosplitting, solar two-step thermochemical cycles, and automaintained methane decomposition were analyzed alongside methane steam reforming with CCS (carbon capture and storage) and electrolysis. Automaintained methane decomposition demonstrated good greenhouse gas emission performance, despite reliance on non-renewable natural gas. Solar two-step thermochemical cycles were promising, contingent on infrastructure materials. Photosplitting with CdS catalysts emerged as the most favorable option, displaying the best performance.

1.1. Aim of this study

The previously mentioned studies show a diversity of configurations for hydrogen production, but most of them focus on assessing global warming potential. However, to the author's knowledge, there is a gap in research regarding the comprehensive analysis of the entire green hydrogen production chain, including exportation, using the ReCiPe methodology. This methodology serves as a technique for conducting impact assessment within a life cycle assessment, converting emissions and resource extractions into environmental impact scores, employing characterization factors for this purpose [24].

This study aims to address this gap by evaluating and comparing the environmental impacts of four different hydrogen production methods aligned with the Chilean Green Hydrogen strategy, employing the ReCiPe methodology. Different process alternatives are compared, varying the base renewable energy supply and the state of the final product (hydrogen). The cases under scrutiny include hydrogen generation from solar energy with compression, hydrogen generation from wind energy with compression, hydrogen generation from solar energy with liquefaction, and hydrogen generation from wind energy with liquefaction.

2

Methodology

2.1. Life cycle assessment

Life cycle assessment is a technique developed to understand and address possible impacts associated with products [25][26]. The primary objective of LCA is to provide insights into the environmental implications of the studied product. In LCAs, the inputs and outputs between a technical system and the environment are quantified. Potential environmental impacts are assessed usually across the complete life cycle of the product, from its origin to its disposal [6]. The Figure 2.1 shows the framework for using LCA tools.

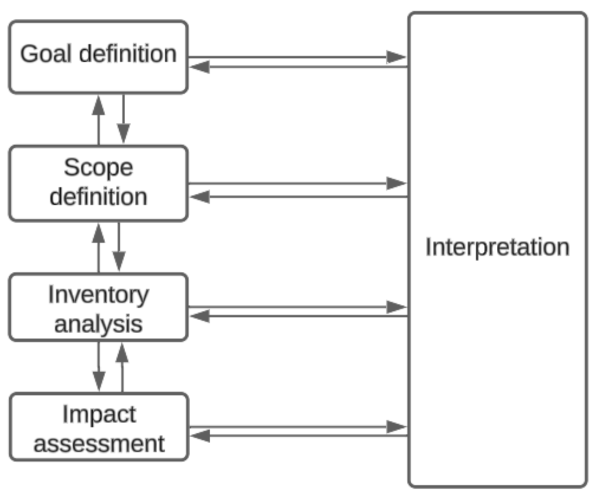


Figure 2.1: Framework of LCA modified from [27].

There are four phases in an LCA study according to the ISO norms [25][26]:

1. The goal and scope definition phase
2. The inventory analysis phase
3. The impact assessment phase

4. The interpretation phase

During the initial stage of conducting a life cycle assessment, which is called the *goal and scope definition* phase, the key aspects such as the system's function, the functional unit (FU), impact categories, and the boundaries are defined. The next stage, known as *life cycle inventory analysis* (LCI), involves collecting data for the primary net flows such as energy, materials, waste, and emissions that enter or leave the system's boundaries. In the third stage, called *life cycle impact assessment* (LCIA), potential environmental impacts are quantified using specific characterization factors that convert elementary flows into impact levels. In the final stage, which is the *interpretation* stage, the study's objectives and scope are taken into account to draw key conclusions [28].

2.2. Goal and scope definition

This research aims to assess and compare the environmental impact of four different hydrogen production processes following the Chilean Green Hydrogen strategy, by utilizing the ReCiPe methodology. The processes being evaluated include hydrogen production from solar energy with compression (Figure 2.2), hydrogen production from wind energy with compression (Figure 2.3), hydrogen production from solar energy with liquefaction (Figure 2.4), and hydrogen production from wind energy with liquefaction (Figure 2.5). Therefore, the functional unit corresponds to the production of 200 [kton/year] of green hydrogen over a 20-year horizon in Chile.

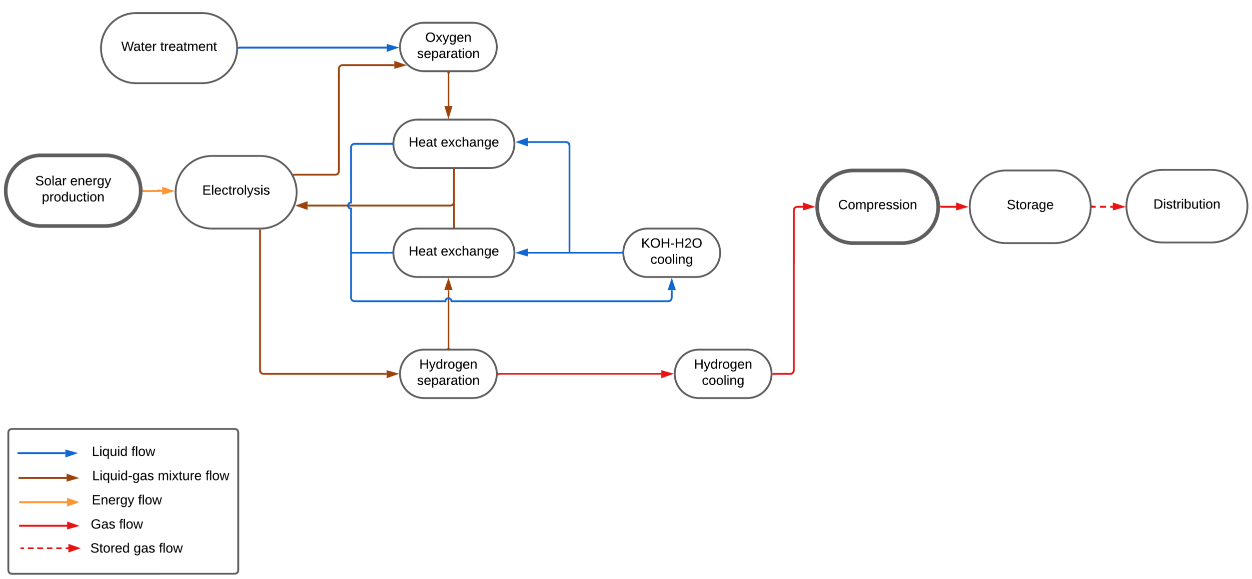


Figure 2.2: Diagram of hydrogen production process from solar energy with compression.

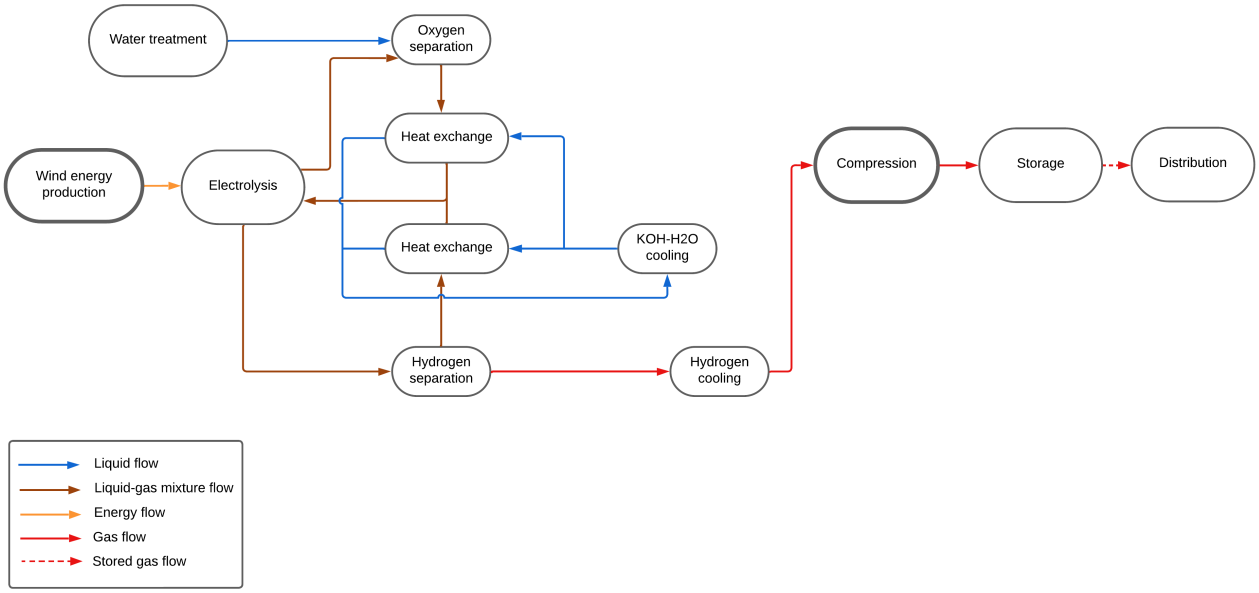


Figure 2.3: Diagram of hydrogen production process from wind energy with compression.

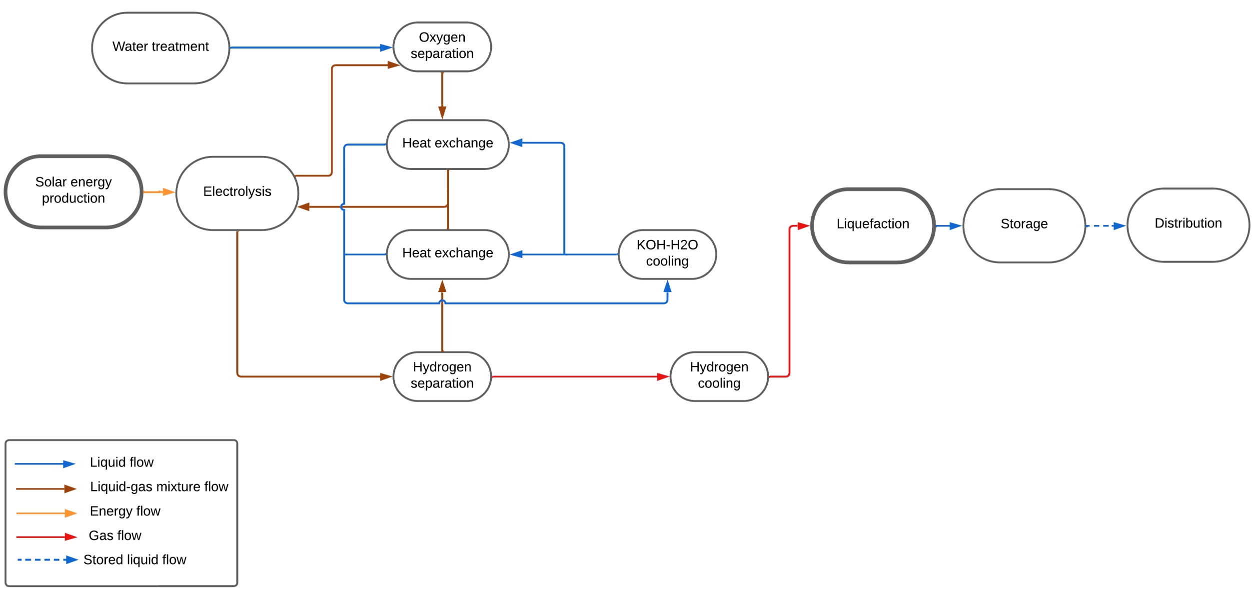


Figure 2.4: Diagram of hydrogen production process from solar energy with liquefaction.

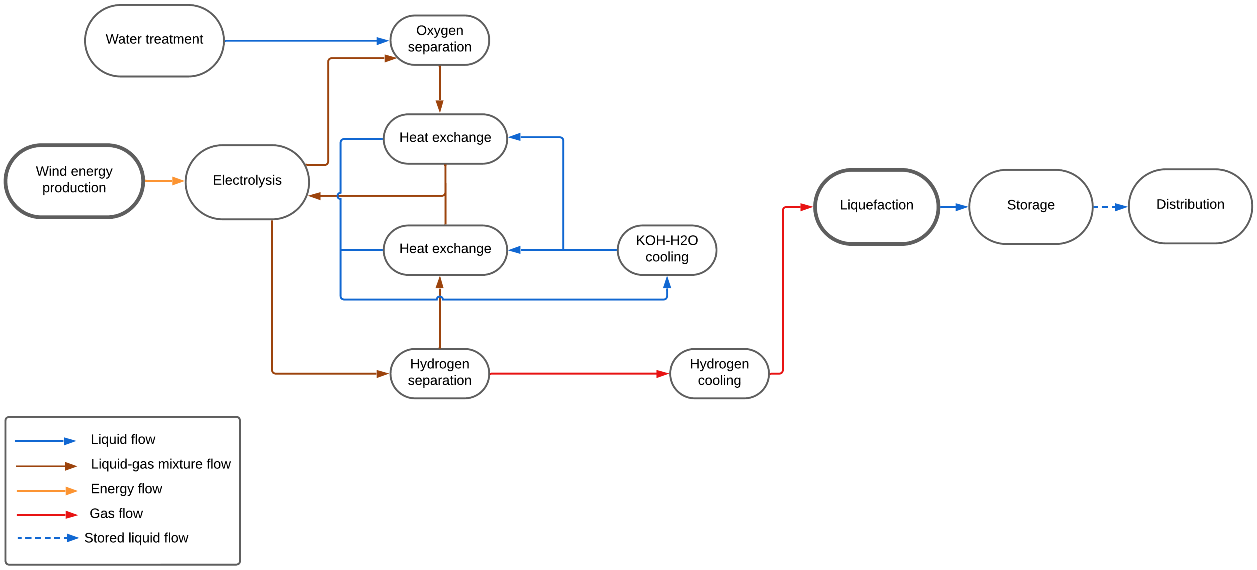


Figure 2.5: Diagram of hydrogen production process from wind energy with liquefaction.

The stages shown in diagrams 2.2, 2.4, 2.3, and 2.5 are described as follows: The Wind energy production and Solar energy production stages are, as their names imply, the stages where energy is generated. The former uses horizontal axis wind turbines, while the latter employs polycrystalline silicon solar panels. During the Electrolysis stage, an alkaline electrolyzer powered by renewable electricity converts water into oxygen and hydrogen. The water treatment stage is carried out using a reverse osmosis desalination plant. In the Oxygen and Hydrogen separation stages, these gases are separated from other remnants in the flow, such as water and the electrolyte (KOH in this case), using gas-liquid separators similar to conventional centrifugal separators. It should be noted that although water is initially directed toward the oxygen separator in the diagrams (as seen in other studies), it actually combines with the outgoing flow from the oxygen separator and is not a direct input to the separation process.

During the KOH-H_2O cooling and Heat exchange stages, the temperature of the remnants is lowered before being reintroduced into the alkaline electrolyzer. The Hydrogen cooling stage aims to reduce the hydrogen temperature for subsequent liquefaction or compression as needed. In the Compression or Liquefaction stage, hydrogen is compressed or liquefied as required. Then, in the Storage stage, the compressed or liquefied hydrogen is stored in tanks appropriate for each state. Finally, in the Distribution stage, the hydrogen is exported to China, Europe, Japan, the United States, and South Korea.

The system boundaries that were taken into consideration for this study are shown in Figure 2.6. However, it is important to note that the energy consumption and waste during the construction phase of the equipment and spare parts were not considered. Additionally, only dismantling to landfill was considered at the end of the equipment's useful life, and not transportation to the landfill, because transportation other than by sea was not taken into account. These considerations were based on the data availability.

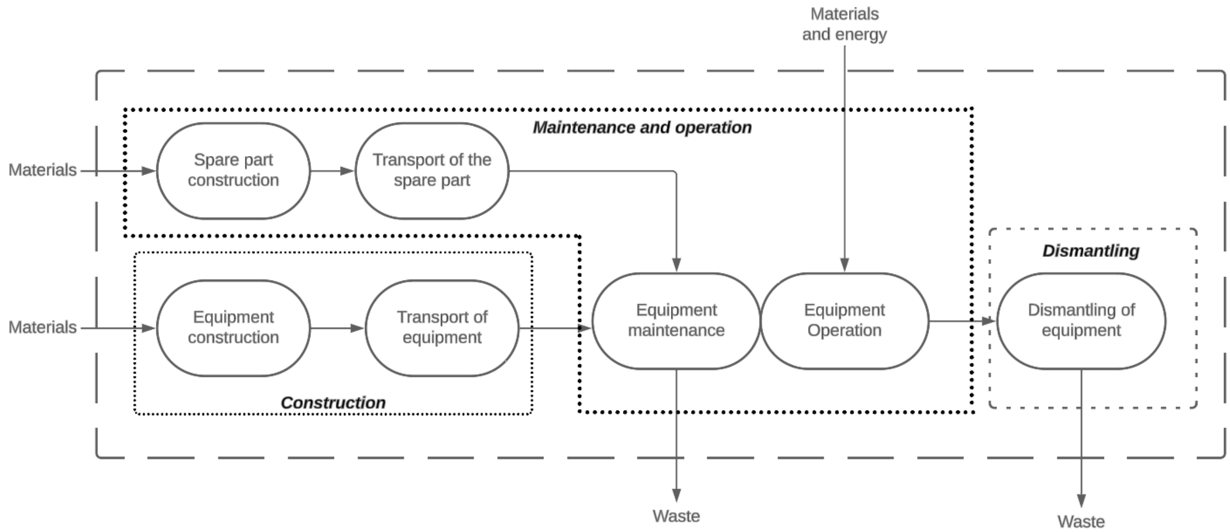


Figure 2.6: System boundaries.

2.3. Life cycle inventory (LCI)

For each scenario, the inventory of the green hydrogen production process is divided in stages, namely: Wind energy production, Solar energy production, Electrolysis, Oxygen separation, Hydrogen separation, Heat exchange, KOH mixing, KOH-H_2O cooling, Hydrogen cooling, Compression, Liquefaction, Storage, Water treatment, and Distribution. Moreover, each of these stages are composed of various phases, such as Construction, Operation, Maintenance, Maintenance waste, and Dismantling waste.

For each hydrogen production method, the material and energy input flows were examined based on the corresponding stage and phase evaluated. The material and energy consumption during each phase was obtained from the literature and adapted to the respective case study. The main references used for this purpose are listed in Table 2.1.

Table 2.1: Main references used to obtain the input flows.

Stage	References
Solar energy production	[29] [30] [31] [32]
Wind energy production	[33] [34]
Electrolysis	[35] [2] [36] [37]
Oxygen separation	[38] [39]
Hydrogen separation	[38] [39]
Heat exchange	[40]
KOH mixing	[41]
KOH-H_2O cooling	[42] [43]
Hydrogen cooling	[44]
Compression	[45]
Liquefaction	[46]
Storage	[47] [48]
Water treatment	[49]
Distribution	[50] [13]

For a more detailed description of the references used in each of the stages according to the phase studied and to observe inventory flows, please refer to the supplementary material of this study located in the Annex A.

2.4. Life cycle impact assessment (LCIA)

This study employs the ReCiPe 2016 (H) life cycle impact assessment (LCIA) method to assess the environmental impacts associated with four different hydrogen production processes. This methodology transforms the life cycle inventory findings into impact category indicators using characterization factors. These factors indicate the contribution of each LCI result to respective indicators. There are two mainstream ways to derive characterization factors: at midpoint level and endpoint level. The term *midpoint* refers to a point along the impact pathway at an intermediate position between the LCI results and the final environmental endpoint. Both approaches complement each other: the midpoint characterization is closely linked to environmental flows and typically involves lower parameter uncertainty, while the endpoint characterization is simpler to interpret in relation to the significance of the aggregated environmental burdens [51][52][53].

The impacts in this study are categorized into endpoint impact categories, which include: terrestrial acidification (expressed as points), terrestrial ecotoxicity (expressed as points), agricultural land occupation (expressed as points), freshwater eutrophication (expressed as points), urban land occupation (expressed as points), freshwater ecotoxicity (expressed as points), natural land transformation (expressed as points), marine ecotoxicity (expressed as points), climate change ecosystems (expressed as points), human toxicity (expressed as points), photochemical oxidant formation (expressed as points), ozone depletion (expressed as points), particulate matter formation (expressed as points), ionizing radiation (expressed as points), climate change human health (expressed as points), fossil depletion (expressed as points), metal depletion (expressed as points), and total (expressed as points). The characterization factors have been obtained from the Ecoinvent database [54].

With regard to the estimation of the various impacts assessed in this study, these impacts are quantified by means of the following equation:

$$Impact\ category\ value = flow[\frac{Unit}{F.U.}] * characterization\ factor[\frac{points}{Unit}] \tag{2.1}$$

3

Results and Discussions

The study has assessed the environmental impacts associated with four alternative green hydrogen production processes, including (i) production from solar energy with hydrogen compression, (ii) production from wind energy with hydrogen compression, (iii) production from solar energy with hydrogen liquefaction, and (iv) production from wind energy with hydrogen liquefaction. The ReCiPe method was to assess the environmental impact of a functional unit equivalent to the production of 200 [kton/year] of green hydrogen over a 20-year horizon in Chile.

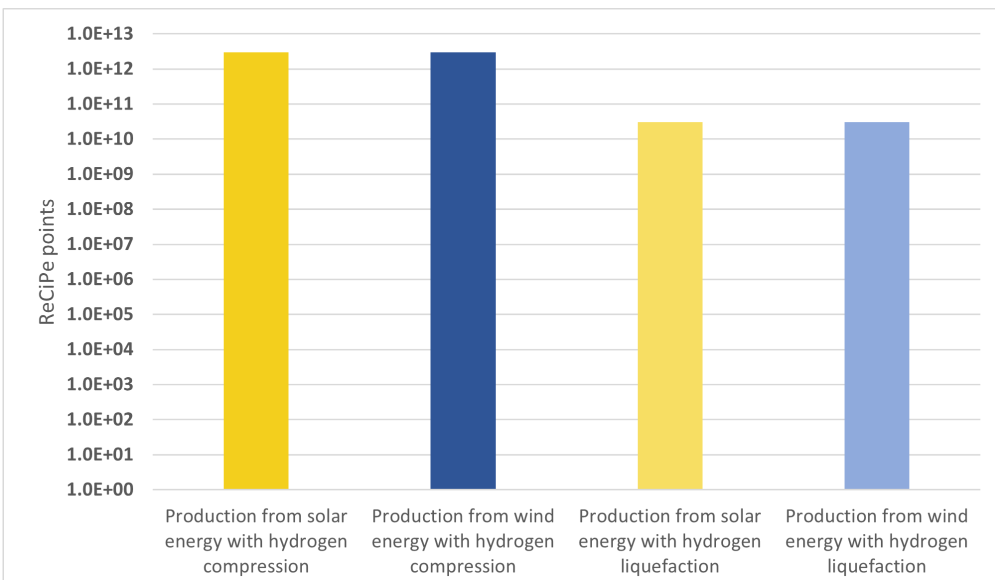
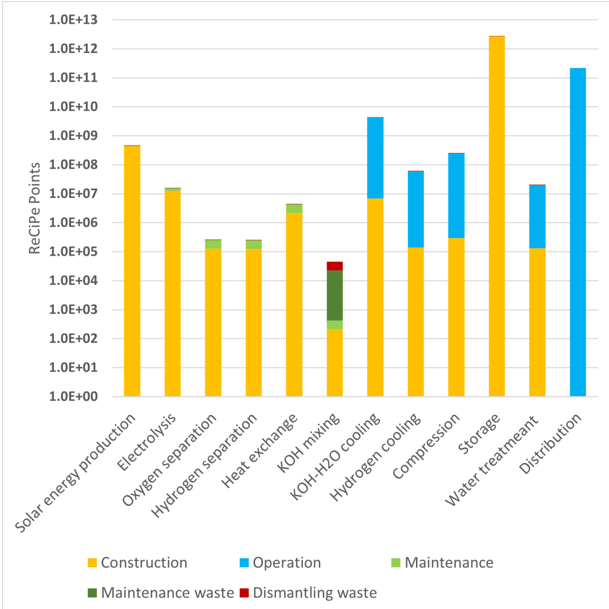


Figure 3.1: ReCiPe points of the four cases studied on a logarithmic scale.

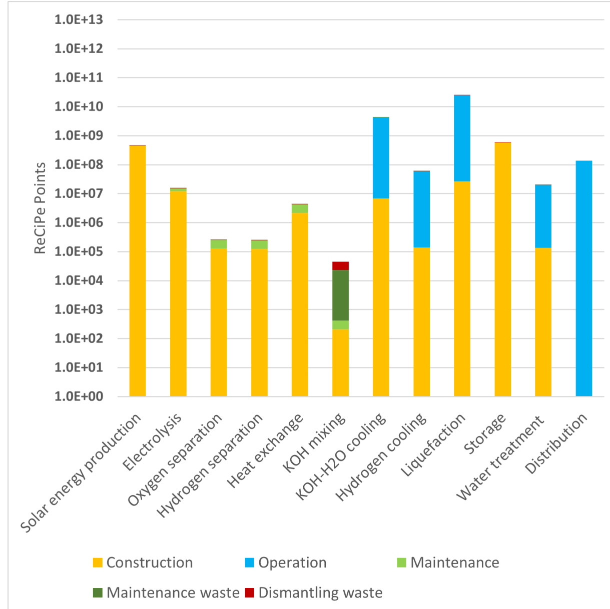
Figure 3.1 visually represents the total ReCiPe points for the four case studies on a logarithmic scale. It is noteworthy that the ReCiPe points attained in hydrogen production from solar energy with compression are approximately 97.4 times the achieved in hydrogen production from solar energy with liquefaction. Furthermore, the ReCiPe points obtained in wind energy hydrogen production with compression are approximately 97.8 times the attained in wind energy hydrogen production with liquefaction.

Additionally, a comparison reveals that the ReCiPe points in hydrogen production from solar energy with compression are approximately 1.00004 times the obtained in hydrogen production from wind energy with compression. Meanwhile, the ReCiPe points in hydrogen production from solar energy with liquefaction are approximately 1.004 times the attained in hydrogen production from wind energy with liquefaction. From these comparisons, it can be said that the difference between these cases is not significant.

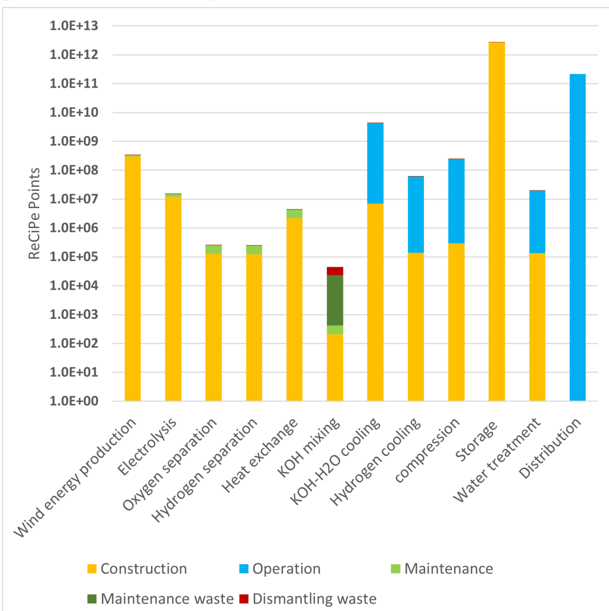
It is assumed that the difference in ReCiPe points between the four cases mentioned above is due to the magnitude of the flows involved and the characterization factors used. It is also noted that the difference between the flows and the characterization factors can be as large as two orders of magnitude.



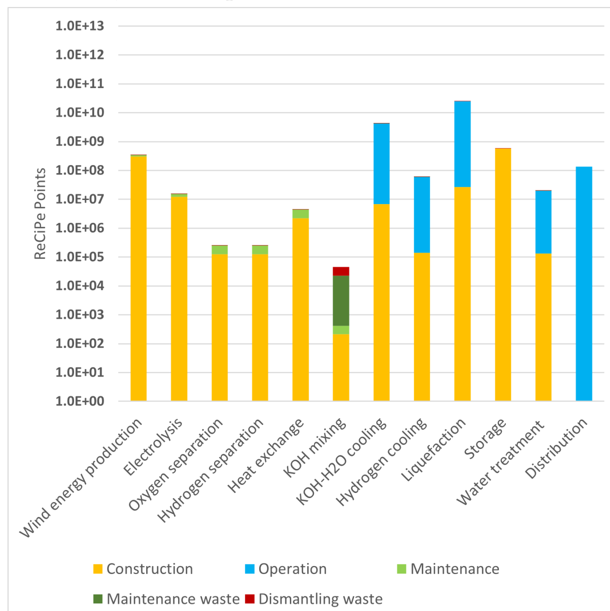
(a) Production from solar energy with hydrogen compression, ReCiPe points.



(b) Production from solar energy with hydrogen liquefaction, ReCiPe points.



(c) Production from wind energy with hydrogen compression, ReCiPe points.



(d) Production from wind energy with hydrogen liquefaction, ReCiPe points.

Figure 3.2: Contribution of each phase to the environmental impact of each stage for the different cases studied on a logarithmic scale.

Figure 3.2 shows the contribution of each phase to the environmental impact of each stage for the different cases studied on a logarithmic scale. In the case of hydrogen production by solar energy with compression, figure 3.2.a shows that the Storage stage has the highest ReCiPe points. As shown in Figure 3.3.a Construction phase contributes the highest percentage of the Storage stage, with a value of more than 97%. It can also be observed that in the Solar energy production stage, the phase that contributes the most to the ReCiPe points is the Construction phase, with around 98%, and in the Compression stage, the phase that contributes the most is the Operation phase, with around 99%.

In the context of hydrogen production through wind energy with compression, as per Figure 3.2.c, the Storage stage also has the highest ReCiPe points. Additionally, Figure 3.3.c highlights that the Construction phase contributes more than 97% to the ReCiPe points of the Storage stage as in the previous case. It can also be noticed that in the Wind energy production stage, the phase that contributes the most is the Construction phase, with around 88% and the Compression stage mirrors the pattern observed in the previous case mentioned.

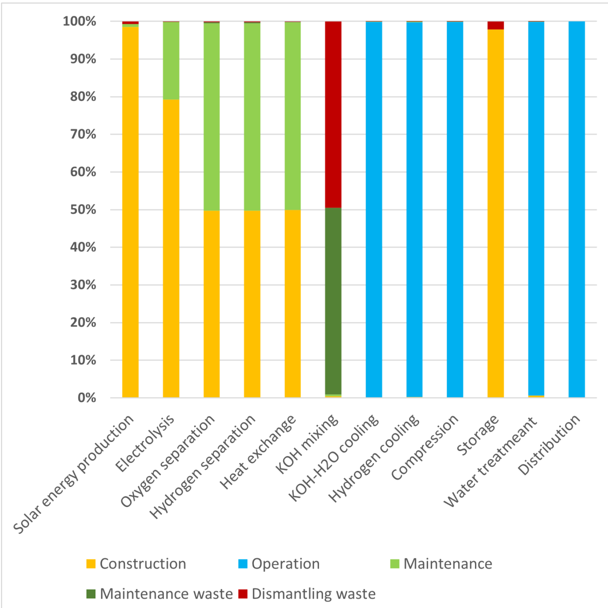
During the Construction phase of the Storage equipment, there are two flows involved: the use of materials and their transportation. In this case, steel is used and the flows involved are 9.837 E+12 [kg] for the amount of steel used and 1.866 E+14 [ton · km] for its transportation. The environmental impact is due to the magnitude of the steel flow used and the characterization factor applied. To reduce the environmental impact, it is necessary to find ways to reduce the consumption of steel. A possible way is to replace steel with materials that have a lower environmental impact or to source the material from a point closer to the installation site. This would reduce the distance per transported mass, thus reducing the environmental impact.

In the matter of hydrogen production via solar energy with liquefaction, according to Figure 3.2.b, the Liquefaction stage emerges with the highest ReCiPe points. Furthermore, Figure 3.3.b underscores that the Operation phase accounts for over 99% of the ReCiPe points in the Liquefaction stage. It can also be noticed that in the Solar energy production stage, the phase that contributes most is the Construction phase with approximately 98%.

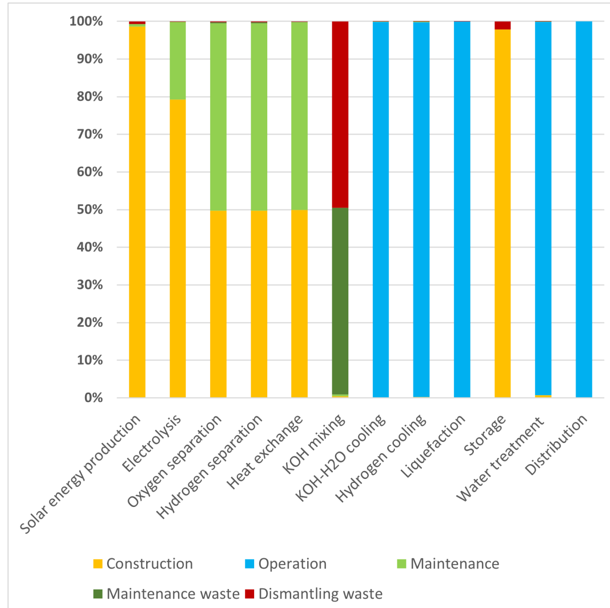
In the case of hydrogen production via wind energy with liquefaction, as shown in Figure 3.2.d, the Liquefaction stage has also the highest ReCiPe points. Additionally, Figure 3.3.d shows that the Operation phase accounts for over 99% of the ReCiPe points during the Liquefaction stage. Furthermore, it can be noticed that in the Wind energy production stage, the phase that contributes most is the Construction phase with approximately 88%.

During the Operation phase of the Liquefaction, the only flow involved is power consumption, which is equivalent to 2.963 E+11 [kWh]. To reduce environmental impact, it is necessary to find ways to reduce power consumption. An alternative is to replace high consumption equipment with low consumption options, which requires a technology change or process intensification.

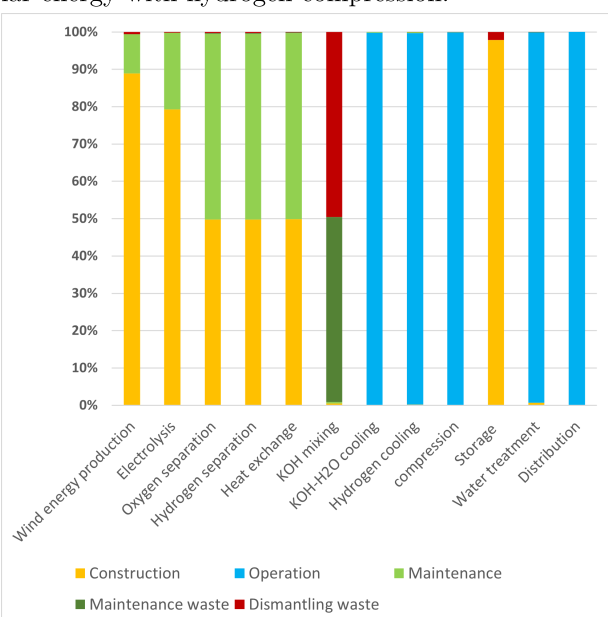
The environmental impacts associated with the Storage stage differ between hydrogen production by liquefaction and compression. This difference is due to the use of different types of storage tanks. In one case, equipment is used to store compressed gases, while in the other, equipment is used to store liquefied gases. These tanks differ not only in the materials used for their manufacture but also in the amount of material required for their construction and the characterization factors applied, which influence the overall environmental impact.



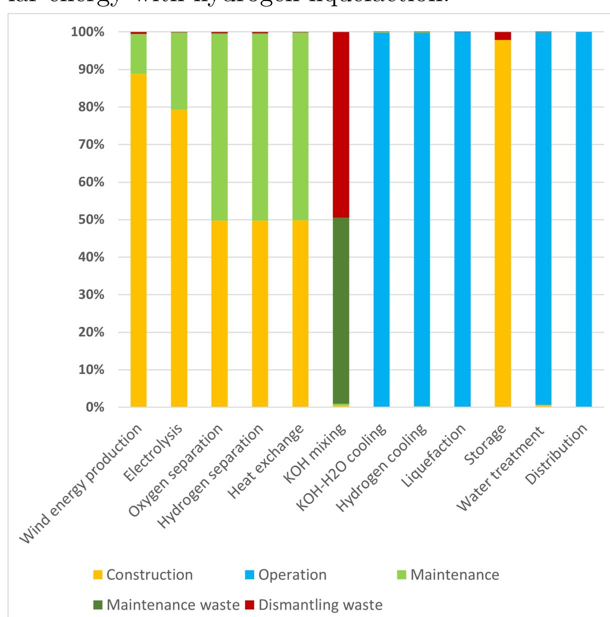
(a) Relative contribution case of production from solar energy with hydrogen compression.



(b) Relative contribution case of production from solar energy with hydrogen liquefaction.



(c) Relative contribution case of production from wind energy with hydrogen compression.



(d) Relative contribution case of production from wind energy with hydrogen liquefaction.

Figure 3.3: Relative contribution of each phase to the environmental impact of each stage for the different cases studied.

The impact categories and their respective contributions, as per the ReCiPe methodology, are depicted in Figure 3.4 on a logarithmic scale. For cases of production from solar energy with hydrogen compression and production from wind energy with hydrogen compression, a detailed examination of the Storage stage reveals that among the categories studied, fossil depletion ranked the highest, followed by climate change, human health. Conversely, categories such as terrestrial ecotoxicity, freshwater eutrophication, marine ecotoxicity, ozone depletion, and ionising radiation had lower ReCiPe points, indicating that they are less significant. For cases of production from solar energy with hydrogen liquefaction and production from wind energy with hydrogen liquefaction, the analysis of impact categories during the Liquefaction stage and their respective contributions shows that among the scrutinized categories, the highest impact was observed in particulate matter formation, followed by fossil depletion and climate change, human health. In contrast, categories such as terrestrial acidification, terrestrial ecotoxicity, freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity, ozone depletion, and ionising radiation exhibited lower ReCiPe points, signifying their relatively lesser significance.

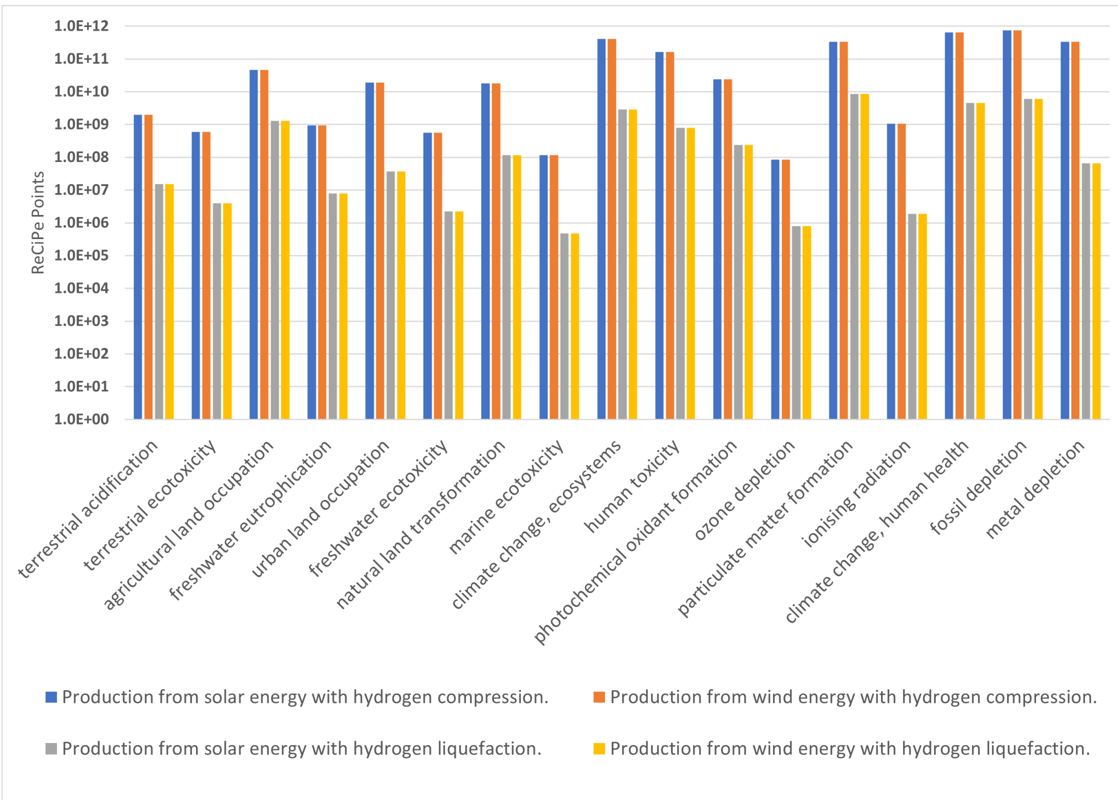


Figure 3.4: ReCiPe points of the impact categories assessed in the study for the different cases on a logarithmic scale.

Based on the previous results, the most favorable scenario is the case of hydrogen production from wind energy with liquefaction. For detailed calculations leading to the presented results, consult the supplementary material of this study located in the Annex A.

From the results obtained, the most environmentally favorable method for the country was identified. However, it is important to note that the selection of production configurations will be influenced by the geography of Chile, which has both solar and wind potentials. In regions with higher solar potential, like the north [55], hydrogen production via solar energy with liquefaction may be more feasible. On the other hand, in regions with higher wind potential, like the south [55], hydrogen production through wind energy with liquefaction may be more favorable. Therefore, while implementing these options, it is essential to consider not only the conducted research but also the geographical characteristics of the country and economic aspects.

This study was conducted in accordance with Chile's Green Hydrogen strategy, which represents the country's initial step towards becoming a low-emission nation. However, this study emphasizes that hydrogen production processes generate emissions, particularly during the construction, operation, maintenance, and dismantling phases of the different stages. Given that this strategy aims to address the global environmental challenge, it is essential to recognize that green hydrogen production has emissions. Therefore, it should prioritize production configurations that minimize them during all the phases, rather than solely focusing on reducing environmental disruption during industrial operation.

It is important to mention that the LCA method hinges on the information available in the selected database for the assessment. Frequently, these databases lack details about specific materials and emissions during the pre-treatment of specialized materials [35]. This introduces a level of uncertainty in the obtained results through LCA. For instance, the composition of the Zirfon material -used in the electrolyzer- as noted in the study by Zhao et al. [35], is confidential regarding its use and manufacturing specifics. To address this confidentiality in our study, we approximated the material to polyphenylene sulfide based on information from [56], which indicated that Zirfon was composed of polyphenylene sulfide fabric.

In all cases, the results of this study were cross-referenced with the existing scientific literature and found to be consistent. This is illustrated in Tables 3.1 and 3.2.

Table 3.1: Comparison between the results obtained and literature.

Study		Present Study (Electrolysis stage) [a]	Zhao et al. [35]
Impact categories	Climate change [kgCO2-Eq/FU]	2 E+02	2 E+02
	Ozone depletion [kg CFC11-eq/FU]	2 E-05	1 E-04
	Terrestrial acidification [kg SO2-eq/FU]	3 E+01	2 E+01
	Freshwater eutrophication [kg P-eq/FU]	3 E-01	2 E-01
	Marine eutrophication [kg N-eq/FU]	5 E-01	1 E-02
	Freshwater ecotoxicity [kg 1,4-DCB-eq/FU]	2 E+01	4 E+01
	Marine ecotoxicity [kg 1,4-DCB-eq/FU]	2 E+01	6 E+01
	Fossil resource scarcity [kg oil-eq/FU]	5 E+01	3 E+01

[a] It is important to note that the results were adjusted to the functional unit used in the comparative study, in this case, 1 m^2 of cell.

Table 3.2: Comparison between the results obtained and literature.

Study	Impact categories: Climate change [kgCO2-Eq/FU]
Present Study (Electrolysis stage)[a]	2 E-01
Koj et al. [57]	6 E-01
Burkhardt et al. [58]	4 E-01
Present Study (Wind energy production stage) [b]	4 E-03
Xu et al. [33]	9 E-03
Present Study (Wind energy production stage) [c]	4 E+00
Burkhardt et al. [58]	8 E-01
Present Study (Solar energy production stage) [d]	1 E+01
Sadeghi et al. [59]	3 E+00
Present Study (Solar energy production stage) [e]	5 E+02
Hong et al. [60]	2 E+03

[a] It is important to note that the results were adjusted to the functional unit used in the comparative study, in this case, 1 kg H_2.

[b] It is important to note that the results were adjusted to the functional unit used in the comparative study, in this case, kWh of electricity generated.

[c] It is important to note that the results were adjusted to the functional unit used in the comparative study, in this case, 1 kg H_2.

[d] It is important to note that the results were adjusted to the functional unit used in the comparative study, in this case, 1 kg H_2.

[e] It is important to note that the results were adjusted to the functional unit used in the comparative study, in this case, 1 kWp multi-Si PV cell production.

When comparing the results of the Electrolysis stage in this study with the one conducted by Zhao et al. [35], both studies showed similar findings in categories such as climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, freshwater ecotoxicity, marine ecotoxicity, and fossil resource scarcity. The results of this study were of a consistent order of magnitude in these categories, except for ozone depletion and marine eutrophication. For the latter two categories, this work showed a lower and higher order of magnitude, respectively. Furthermore, a comparison with the findings from the studies by Koj et al. [57] and Burkhardt et al. [58], reveals results consistent with the magnitude observed in the present study.

In terms of environmental impact, a comparison was made between the results obtained for the Wind and Solar energy production stages and literature. In the category of climate change, the results for the Wind energy production stage are consistent with those reported in Xu et al. [33] and show a similar order of magnitude. However, when contrasted with the results of Burkhardt et al. [58], this study shows an order of magnitude higher than that reported in the literature. Concerning the Solar energy production stage, the results obtained differ by an order of magnitude from those in Sadeghi et al. [59], specifically registering an order of magnitude higher. Conversely, compared to the results in Hong et al. [60], the results in this work are an order of magnitude lower than reported in the literature.

The difference between this study and the literature is assumed to be due to the magnitude of the flows, the flow materials, and the characterization factors used. For detailed calculations leading to the presented results, consult the supplementary material of this study located in the Annex A.

4

Conclusions

4.1. Summary of the Thesis and Key Contributions

The main objective of this work was to present the results of a comprehensive LCA of hydrogen production using four production pathways. Production from solar energy with hydrogen compression, production from wind energy with hydrogen compression, production from solar energy with hydrogen liquefaction, and production from wind energy with hydrogen liquefaction were evaluated. A total of 17 impact categories and a total were assessed, which were counted in points according to the ReCiPe methodology.

In terms of overall environmental impact, hydrogen production from wind energy with liquefaction has the lowest ReCiPe points and thus the lowest environmental impact. The primary environmental impact in this case is caused by the Operational phase of Liquefaction, mainly due to the high power consumption during this phase, amounting to 2.963 E+11 [kWh]. Therefore, it is crucial to replace or optimize the machines involved in this phase to enhance their electrical efficiency and subsequently reduce electricity consumption, ultimately leading to a reduction in environmental impact. Regardless of how hydrogen is produced, minimizing metal and energy consumption can significantly reduce its environmental impact.

It is worth noting that the difference between producing hydrogen from solar or wind energy -using the same subsequent production process- is not significant in the context of the four cases evaluated in this study. However, if the change in the production process is in the way the hydrogen is treated for storage, i.e. whether it is compressed or liquefied, there is a significant difference. Therefore, there is a perceived need to make technological advancements in compression technology to reduce its environmental impact.

Although the results favored hydrogen production based on wind energy with liquefaction, it is essential to take into account Chile's diverse geography since the study is focused on this country. Therefore, factors such as geographical or economic feasibility may make it more viable to establish hydrogen production using a different process in certain areas.

It should be noted that the National Strategy serves as a starting point for Chile's transition to a low emission country. As the results of this study show, hydrogen production methods are not emission-free, as the infrastructure required to produce and transport hydrogen generates emissions during its construction, operation, maintenance, and dismantling. Therefore, the strategy should not only focus on industrial development that is compatible with its environmental surroundings during the operation of the industry but also consider the entire life cycle of the process. Adopting this approach would help minimize environmental impacts throughout the process.

Finally, it is important to mention that this study was limited by the availability of information, requiring assumptions to be made. More data is needed, particularly regarding the exact composition of the electrolyzer membranes. However, when comparing the results obtained with the existing literature, it was observed that they were consistent. Therefore, it is concluded that the assumptions made do not significantly affect the system as a whole. Furthermore, it is important to emphasize that this study lays the groundwork for a new data set to support future research in the field of green hydrogen production.

4.2. Future Recommendations

To improve the study, it is suggested to collect primary data directly from companies or individuals involved in the production of green hydrogen in Chile. This method would reduce uncertainties resulting from data estimates. Moreover, broadening the scope of the study to include more equipment types, such as various compressor models or solar panels, would lead to a more extensive insight into different configurations of production plants.

It is also recommended that an improvement would be to include recycling, particularly in the dismantling phase, by not only considering landfill as the final destination but also evaluating recycling opportunities.

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ANNEXES

Annex A. Supplementary data

Supplementary data to this article can be found in https://1drv.ms/x/s!Ap4g5ZNdKmphbS5ql4_-wMvcVaA?e=AyHAas. The detailed quantification of flows and impacts (LCI and LCIA) conducted for this study is available here.

The document contains 20 sheets entitled:

- References
- 1.Case SPP(Materials)
- 1.Case SPP(Balance)
- 1.Case WPP(Materials)
- 1.Case WPP(Balance)
- 1.Impact of SPP case
- 1.Impact of WPP case
- 1.Summary of the impact
- 1.Graphs of SPP case
- 1.Graphs of WPP case
- 2.Case SPP(Materials)
- 2.Case SPP(Balance)
- 2.Case WPP(Materials)
- 2.Case WPP(Balance)
- 2.Impact of SPP case
- 2.Impact of WPP case

- 2.Summary of the impact
- 2.Graphs of SPP case
- 2.Graphs of WPP case
- FINAL GRAPHS

The following is a description of the contents of the sheets listed above.

References
This sheet lists all references used in the document's construction.

1.Case SPP(Materials)
This sheet contains calculations quantifying the use of materials for the construction, maintenance, and dismantling of equipment for hydrogen production from solar energy with compression. It is important to note that throughout the calculations, it was assumed that there were no losses of mass or energy. The material consumption for each piece of equipment was derived from bibliographic research and adapted to the case study. One of the most frequently used equations in this sheet is:

$$Total\ Material = Material\ per\ equipment[\frac{Unit}{equipment}] * number\ of\ equipment[equipment] \tag{A.1}$$

1.Case SPP(Balance)
This sheet includes calculations for quantifying the use of inputs during the operation of equipment, in addition to determining the number of units required for hydrogen production from solar energy with compression. As with the previous sheet, it was assumed that there were no losses of mass or energy. The input consumption for each piece of equipment was derived from bibliographic research and adapted to the case study. A commonly used equation here is:

$$Total\ Material = Material\ per\ equipment[\frac{Unit}{equipment}] * number\ of\ equipment[equipment] \tag{A.2}$$

1.Case WPP(Materials)
This sheet contains calculations for quantifying the use of materials for the construction, maintenance, and dismantling of equipment for hydrogen production from wind energy with compression. As with the previous cases, it was assumed that there were no losses of mass or energy. The material consumption for each piece of equipment was derived from bibliographic research and adapted to the case study. The primary equation used is:

$$Total\ Material = Material\ per\ equipment[\frac{Unit}{equipment}] * number\ of\ equipment[equipment] \tag{A.3}$$

1.Case WPP(Balance)

This sheet includes calculations for quantifying the use of inputs during the operation of equipment, as well as determining the number of units required for hydrogen production from wind energy with compression. It was assumed that there were no losses of mass or energy. The input consumption for each piece of equipment was derived from bibliographic research and adapted to the case study. The primary equation used is:

$$Total\ Material = Material\ per\ equipment[\frac{Unit}{equipment}] * number\ of\ equipment[equipment] \tag{A.4}$$

1.Impact of SPP case

This sheet quantifies the environmental impacts for the case of hydrogen production from solar energy with compression, using the following equation:

$$Impact\ category\ value = flow[\frac{Unit}{F.U.}] * characterization\ factor[\frac{points}{Unit}] \tag{A.5}$$

It is important to note that there are a total of 228 flows involved in this case.

1.Impact of WPP case

This sheet quantifies the environmental impacts for the case of hydrogen production from wind energy with compression, using the following equation:

$$Impact\ category\ value = flow[\frac{Unit}{F.U.}] * characterization\ factor[\frac{points}{Unit}] \tag{A.6}$$

A total of 226 flows are considered in this case.

1.Summary of the impact

This sheet summarizes the environmental impacts described in the previous two sheets, offering a more compact visualization.

1.Graphs of SPP case

This sheet visually presents the environmental impacts of hydrogen production from solar energy with compression.

1.Graphs of WPP case

This sheet visually presents the environmental impacts of hydrogen production from wind energy with compression.

2.Case SPP(Materials)

This sheet contains calculations quantifying the use of materials for the construction, maintenance, and dismantling of equipment for hydrogen production from solar energy with liquefaction. Assumptions regarding no losses of mass or energy apply here as well. Material consumption is adapted from bibliographic research to the case study. The primary equation used is:

$$Total\ Material = Material\ per\ equipment[\frac{Unit}{equipment}] * number\ of\ equipment[equipment] \tag{A.7}$$

2.Case SPP(Balance)

This sheet includes calculations for quantifying the use of inputs during the operation of equipment and determining the number of units required for hydrogen production from solar energy with liquefaction. Assumptions regarding no losses of mass or energy apply. Input consumption is adapted from bibliographic research to the case study. The primary equation used is:

$$Total\ Material = Material\ per\ equipment[\frac{Unit}{equipment}] * number\ of\ equipment[equipment] \tag{A.8}$$

2.Case WPP(Materials)

This sheet contains calculations quantifying the use of materials for the construction, maintenance, and dismantling of equipment for hydrogen production from wind energy with liquefaction. As with previous sheets, assumptions regarding no losses of mass or energy are made. Material consumption is adapted from bibliographic research to the case study. The primary equation used is:

$$Total\ Material = Material\ per\ equipment[\frac{Unit}{equipment}] * number\ of\ equipment[equipment] \tag{A.9}$$

2.Case WPP(Balance)

This sheet includes calculations for quantifying the use of inputs during the operation of equipment and determining the number of units required for hydrogen production from wind energy with liquefaction. It was assumed that there were no losses of mass or energy. Input consumption is adapted from bibliographic research to the case study. The primary equation used is:

$$Total\ Material = Material\ per\ equipment[\frac{Unit}{equipment}] * number\ of\ equipment[equipment] \tag{A.10}$$

2.Impact of SPP case

This sheet quantifies the environmental impacts of hydrogen production from solar energy with liquefaction using the following equation:

$$Impact\ category\ value = flow[\frac{Unit}{F.U.}] * characterization\ factor[\frac{points}{Unit}] \tag{A.11}$$

A total of 236 flows are involved in this case.

2.Impact of WPP case

This sheet quantifies the environmental impacts of hydrogen production from wind energy with liquefaction using the following equation:

$$Impact\ category\ value = flow[\frac{Unit}{F.U.}] * characterization\ factor[\frac{points}{Unit}] \tag{A.12}$$

A total of 234 flows are involved in this case.

2.Summary of the impact

This sheet provides a summary of the environmental impacts described in the previous two sheets, offering a more compact visualization.

2.Graphs of SPP case

This sheet visually presents the environmental impacts of hydrogen production from solar energy with liquefaction.

2.Graphs of WPP case

This sheet visually presents the environmental impacts of hydrogen production from wind energy with liquefaction.

FINAL GRAPHS

This sheet contains detailed graphs specifically designed to visually represent this study's comprehensive results and findings, allowing for easier interpretation and analysis of the data presented.