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Subject

**“ Environmental Impacts of Electrochemical Hydrogen Production Powered by Solar-Generated Electricity “**

Keywords: alkaline water electrolysis; hydrogen production; life cycle assessment; global warming potential; concentrated solar power; photovoltaics; renewable energies

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# I. Acknowledgment

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# II. Abstract

The transition to renewable energy sources is imperative for mitigating climate change and achieving a sustainable future, as also defined in the Brundtland report. Hydrogen, defined as a "clean, reliable and affordable energy carrier", holds great promise when produced using renewable energy sources, particularly solar energy. This study employs a life cycle assessment (LCA) to evaluate the environmental implications of electrochemical hydrogen production with an alkaline electrolyzer powered by solar energy in three locations with abundant sunlight: Spain, Saudi Arabia, and Chile. The analysis encompasses a range of solar energy configurations, including CSP/PV hybrids, CSP tower plants, and PV systems. The findings indicate that the electricity utilized to power the electrolyzer constitutes the primary contributor to emissions and environmental impacts. Among the various solar energy configurations, the hybrid CSP/PV system exhibited the most favorable environmental performance when solar irradiation exceeded $2{,}100\ \frac{kWh}{m^2}$ per year. The global warming potential (GWP) of the electrochemical hydrogen from the combined CSP/PV energy source is approximately $0.57\ \frac{kg\ CO_2-eq}{kg\ H_2}$ for Chile and $1.59\ \frac{kg\ CO_2-eq}{kg\ H_2}$, for Spain. The emissions are reduced approximately 94.5 % compared to the conventional hydrogen production menthod SMR ($10.40\ \frac{kg\ CO_2-e}{kg\ H_2}$). These outcomes underscore the pivotal role of location and solar irradiation in shaping environment impact. The study's findings underscore the significance of upstream processes in the life cycle, particularly in the context of steel production and electricity mixes with a substantial contribution from fossil fuels. These results show the critical importance of optimizing electricity sources and material inputs to minimize the environmental impact of hydrogen production. The insights derived from this study can serve as a guide for stakeholders in selecting sustainable hydrogen production pathways, thereby contributing to the realization of global climate goals and the Sustainable Development Goals (SDGs).

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# VI. List of Abbreviations

ADP ........ abiotic depletion potential
AEL ........ alkaline electrolyzer
AEM ........ alkaline exchange membrane
CCS ........ carbon capture and storage
Co ........ cobalt
$CO_2$ ........ carbon dioxide
CRM ........ critical raw material
c-Si ........ crystalline silicon
CSP ........ concentrated solar power
CU ........ copper
DCB ........ dichlorobenzene
DLR ........ Deutsches Zentrum für Luft- und Raumfahrt
DNI ........ direct normal irradiation
EoL ........ end of life
Fe ........ iron
GHG ........ greenhouse gas
GWP ........ global warming potential
$H_2$ ........ hydrogen
$H_2O$ ........ hydrogen dioxide
HTP ........ human toxicity potential
IRENA ........ international renewable energy agency
ISO ........ international organization for standardization
KOH ........ potassium hydroxide
LCA ........ life cycle assessment
LCI ........ life cycle inventory
LFR ........ linear Fresnel reflector
LT ........ long term
MAEDP ........ marine aquatic ecotoxicity potential
MDP ........ metal depletion potential

Ni ........................................................ nickel
$O_2$ ........................................................ oxygen
OER ........................................................ oxygen evolution reaction
$OH^-$ ........................................................ hydroxide ions
PEM ........................................................ proton exchange membrane
PGM ........................................................ platinum group metals
PV ........................................................ photovoltaics
PVC ........................................................ polyvinylchloride
PVPS ........................................................ photovoltaic power systems programme
RoW ........................................................ rest of the world
SLCA ........................................................ social life cycle assessment
SMR ........................................................ steam methane reforming
SOEC ........................................................ solide oxide electrolyzer cell
SS ........................................................ stainless steel
TAETP ........................................................ terrestrial ecotoxicity
TES ........................................................ thermal energy storage
UBA ........................................................ Umweltbundesam*t*
USD ........................................................ united states dollar
VOC ........................................................ volatile organic compounds

# 1. Introduction

Anthropogenic climate change represents the most critical threat facing humanity in the present era. To ensure the continued existence of future generations on Earth, it is important to alter our way to economize. The emissions of greenhouse gas, in addition to the environmental impacts on water and land, significantly influences anthropogenic climate change and, consequently, our future. The planetary boundaries concept delineates this effect, and it is evident that six out of nine planetary boundaries have already been transgressed, exceeding the safe operating space for humanity (Richardson et al., 2023). In light of these global challenges the switch to renewable energy sources has become an urgent priority. Hydrogen is increasingly recognized as a versatile and sustainable energy carrier, especially when produced using renewable energy sources. Solar energy, due to it's enormous potential (see Figure 1), is a promising energy source, especially in regions with abundant sunlight, where its yield can support large-scale hydrogen production.

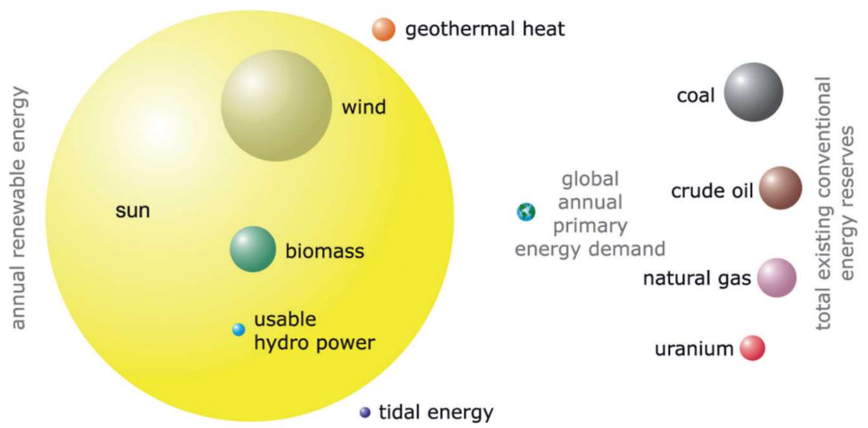


*Figure 1: Comparison of annual renewable energy available and global energy requirements with the total existing conventional energy sources on Earth (Quaschning, 2020b).*

However, the environmental impact of producing hydrogen from solar energy remains a critical area of study. This is not only to mitigate the adverse effects on the climate, but also to contribute to the sustainable development goals (SDGs). Conducting a comprehensive life cycle assessment (LCA) is imperative to evaluate these impacts and identify potential trade-offs. Furthermore, comparing analysis of the environmental performance of solar-powered hydrogen production across various locations and with other renewable energy sources can provide valuable insights for decision-makers and stakeholders. This comparative analysis can contribute to the fulfillment of certain SDGs, such as climate action or responsible consumption and production, which can lead to a decisive contribution to a sustainable future (Miranda et al., 2023).

This thesis aims to assess the environmental impacts of electrochemical hydrogen production through an alkaline electrolyzer powered by solar energy in three sun-rich locations. Using the LCA methodology, the study evaluates the entire life cycle of the process, from solar energy generation to hydrogen production, and compares the results with alternative renewable solar energy sources. The primary research inquiries that will be examined are as follows: First, the environmental impacts of solar-powered hydrogen production is examined across different locations (Spain, Saudi Arabia and Chile). Secondly, the inquiry focuses on the influence of the solar energy source, categorizing it as a combination of CSP/PV hybrid, CSP tower plant and PV system, on the impact categories. This makes it possible to analyze, which component of the electrochemical hydrogen production pathway exerts the greatest influence on the impact categories.

To address these research questions, this thesis adopts an LCA methodology after ISO 14040 and 14044 to evaluate the environmental impacts of electrochemical hydrogen production powered by solar energy. The study systematically assesses the environmental performance of different configurations and locations, the study aims to identify the most critical impact factors and potential areas for optimization.

The thesis is organized as follows: Chapter 2 provides a detailed review of the theoretical background, including the relevance of hydrogen and the fundamentals of LCA. Chapter 3 delineates the methodological framework of the study, encompassing the LCA system boundaries, the life cycle inventory, and the assessment with the findings of the comparative analysis. In this chapter, the most significant contributors of environmental impacts will be discussed. Finally, the concluding chapter synthesizes the key insights and recommendations for the future research directions.

# 2. Basics

The following section presents an overview of the fundamental principles of hydrogen, electrolyzers, and renewable solar energy sources. These main topics are examined within the context of their historical development and the various technological approaches that have emerged. Additionally, it is essential to identify the most suitable water electrolysis option for the bachelor’s thesis, given the multitude of available techniques.

## 2.1. Hydrogen

### *2.1.1. Hydrogen basics*

There are various processes to produce hydrogen; it can be generated from; water, biomass, natural gas via steam methane reforming, methane pyrolysis or coal via gasification (Maniscalco et al., 2024).

Hydrogen is the most plentiful element in the universe and is found on Earth primarily in water and in organic matter (Gielen et al., 2019). It is listed first in the periodic table of elements and the lightest gas. In addition, hydrogen is the most prevalent element on Earth, comprising approximately 50 % of the Earth crust. The element was first discovered during researching metals and acids in 1766 by the English scientist Henry Cavendish. The element was subsequently named hydrogen by Antoine Lavoisier, deriving the name from the Greek word ‘hydro gignomai’ meaning ‘creating/becoming water’ and also on the Latin word ‘hydrogenium’ meaning ‘water producer’ (Sterner and Stadler, 2019). The first instance of hydrogen production via water electrolysis was achieved by the English scientist Nicholson and Carlisle in 1800. Afterwards, it was employed in a multitude of additional processes, including the propulsion of balloons (Zepplins) and also fuel cells (Boudellal et al., 2018).

### 2.1.2. Hydrogen production methods and role of energy transition

Today hydrogen is more interesting than ever because it has huge potential as a replacement for fossil fuels in different sectors. Hydrogen is relevant as a fuel itself, for example for the electricity generation but it will be an important element to produce sustainable fuels via methanol synthesis or Fischer-Tropsch synthesis (Sterner and Stadler, 2019). One of the most challenging problems is, that only 4 % of today's hydrogen is produced by water electrolysis. Most hydrogen is still produced from natural gas or liquid hydrocarbons, releasing carbon dioxide, which makes the produced hydrogen not sustainable at all (IRENA, 2021). Possible ways of producing $CO_2$-free or $CO_2$-neutral hydrogen are water electrolysis using renewable energies or methane pyrolysis. If this hydrogen is sustainable still has to be investigated.

However, electrochemical hydrogen production has also environmental impacts which should not be neglected. For example, greenhouse gas emission from the production of the used materials, as well as metal depletion. Most electrolysis processes use critical and strategic materials which have also a significant environmental impact (Eikeng et al., 2024a). Furthermore, the electricity supply is also an essential parameter when evaluating electrolytic hydrogen production (Burkhardt et al., 2016; Koj et al., 2017). If the hydrogen is produced by a specific grid electricity mix which includes a big share of fossil energy generation, then the hydrogen can even have a higher impact than hydrogen from fossil energy sources.

## 2.2. Electrochemical hydrogen production

Several types of commercially available electrolysis technologies can be used to produce electrolytic hydrogen. Water electrolysis is an electrochemical process that employs electricity to split water molecules into hydrogen ($H_2$) and oxygen ($O_2$). Depending on the specific electrolysis technology, employed hydrogen with an ultra-high purity level (> 99.999 %) can be obtained. If the source of electricity for the used electrolysis process is a renewable energy source then the process can be regarded as an environmentally friendly option (Bailón et al., 2021). Because of the huge potential, it is especially promising to use solar energy as a renewable energy source.

Figure 2 shows the four commercially available water electrolyzer technologies which are: alkaline electrolysis (AEL) and proton exchange membrane (PEM) electeolysis, anion exchange membrane (AEM) electrolysis and solid oxide cell (SOEC) electrolysis.

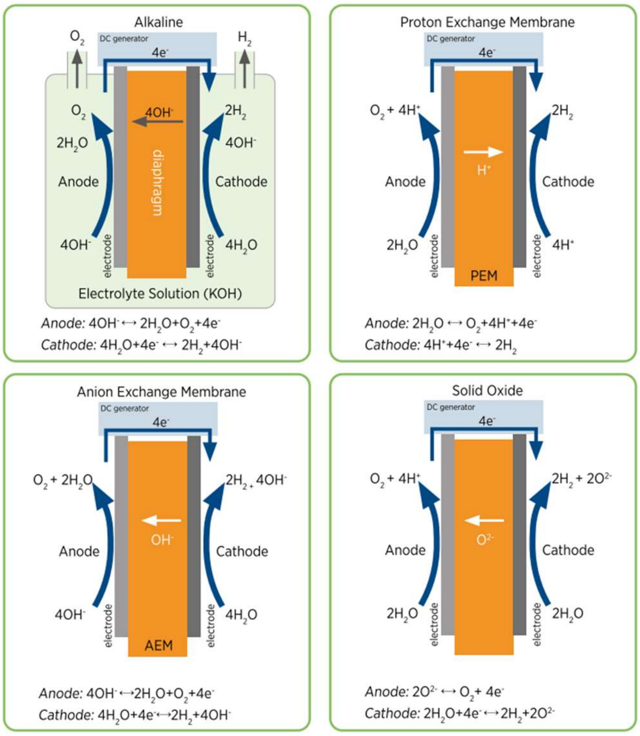


*Figure 2: Overview of various electrolysis technologies (IRENA, 2020a).*

In 2020, the installed capacity of AEL was 61 %, which signified that it was the most developed electrolysis type, while PEM had a 31 % share (IEA, 2021a). Since the beginning of the 20$^{th}$ century, the alkaline water electrolyzer has been commercialized and can be considered as a well-established technology (LeRoy, 1982). Additionally, PEM is pervasively utilized technology with a substantial presence within the electrolysis domain (Bailón et al., 2021). Both SOEC and AEM have a high potential and a promising future. However, as significant challenge is that these two types of electrolysis are less mature technologies in comparison to PEM and AEL, with only a limited number of companies and research institutions involved in their manufacture and commercialization (IRENA, 2020a). That is why in the following PEM and AEL electrolysis are analyzed in more detail in order to ascertain which of these is more suited to the objectives of this thesis.

As previously stated, the production of hydrogen via water electrolysis can be more environmentally friendly if the energy is derived from renewable sources. However, electrochemical hydrogen production has still environmental impacts which should not be neglected, even when the energy source is renewable. The environmental impact of the materials in question remains a pertinent issue, with particular focus on the greenhouse gas emission generated during the production process and the depletion of metals. Most electrolysis system require critical and strategic materials which have also a significant environmental impact (Eikeng et al., 2024a). Furthermore, LCA studies showed that the electricity supply is also an essential parameter when evaluating electrolytic hydrogen production (Burkhardt et al., 2016) (Koj et al., 2017). If the hydrogen is produced by a specific grid electricity mix which includes a high share of fossil energy sources, then the electrolytic hydrogen can even have a higher impact than hydrogen directly produced from fossil sources.

A more detailed examination of the material demand from AEL and PEM reveals that AEL may be more environmentally friendly in this category than PEM due to the relatively limited amount of critical and strategic raw materials required for AEL. According to the IRENA, critical materials represent a significant limitation for PEM (IRENA, 2020b). In comparison to PEM, AEL exhibits a reduced level of critical materials, as the state-of-the-art commercial PEM necessitates the use of titanium, platinum, copper and iridium (Eikeng et al., 2024a). Another environmental advantage of AEL is that the electrode does not consist of noble materials (Schmidt et al., 2017).

A number of LCA studies have demonstrated that the global warming potential of hydrogen produced through AEL is in general lower than that produced trough PEM. The GWP of AEL is reported to be between 0.11 and 4.32 $\frac{kg\ CO_2{-}E}{kg\ CO_2}$, depending on the location, electricity source, and the system boundaries of the chosen system. In comparison, the GWP of PEM is between 0.09 and 31.3 $\frac{kg\ CO_{2-eq}}{kg\ h_2}$, with the specific value depending on the location, electricity source and also on the determined system boundary such as "cradle to gate" (Maniscalco et al., 2024).

Beside the aforementioned environmental advantages of AEL, there is a major economic advantage. The capital costs for an AEL system above 10 MW system are 500-1000 $\frac{USD}{kW}$ compared to 700-1400 $\frac{USD}{kW}$for PEM. However, a significant drawback of AEL is the relatively low $H_2$ purity, which ranges from 99.5 to 99.9998 %. The PEM has a hydrogen purity of 99.9-99.9999 % (Shiva Kumar and Lim, 2022). Nevertheless, for the purposes of the bachelor's thesis, the $H_2$ purity is not a determining factor, given that the use of hydrogen is outside the system boundary.

In light of the prevailing economic as well as the environmental advantages of AEL, the selected electrolysis type for electrolytic hydrogen production will be AEL. Moreover, Maniscalco et al. demonstrate that there is a deficiency in analysis of AEL LCA, as the existing body of literature on electrolysis LCAs predominantly focuses on PEM (Maniscalco et al., 2024).

### *2.2.1 Alkaline electrolysis*

As previously stated in section 2.2, AEL is a well-established technology with a global reach, capable of supplying industrial hydrogen at multi-megawatt levels in a variety of industrial contexts (Kuckshinrichs et al., 2017). The process of electrolytic water splitting was first discovered over two centuries ago and the world's largest pressurized electrolysis power plant is located in Egypt with a rated power of 156 MW and a $H_2$ production of 33,000 $\frac{m^3}{h}$ (Sterner and Stadler, 2019).

Figure 3 illustrates the fundamental operation and configuration of an alkaline electrolyzer cell. The primary component of an AEL is potassium hydroxide (KOH), which has a concentration of 20 to 40 % depending on the required weight of the water ($H_2O$) (Sterner and Stadler, 2019). In comparison to other electrolyzer technologies, such as

SOEC, alkaline water electrolyzers operate at relativity low temperatures (30-70°C) (Shiva Kumar and Lim, 2022). The water KOH mixture circulates through the two half cells, which are separated by an ion conduction membrane, as illustrated in Figure 3.

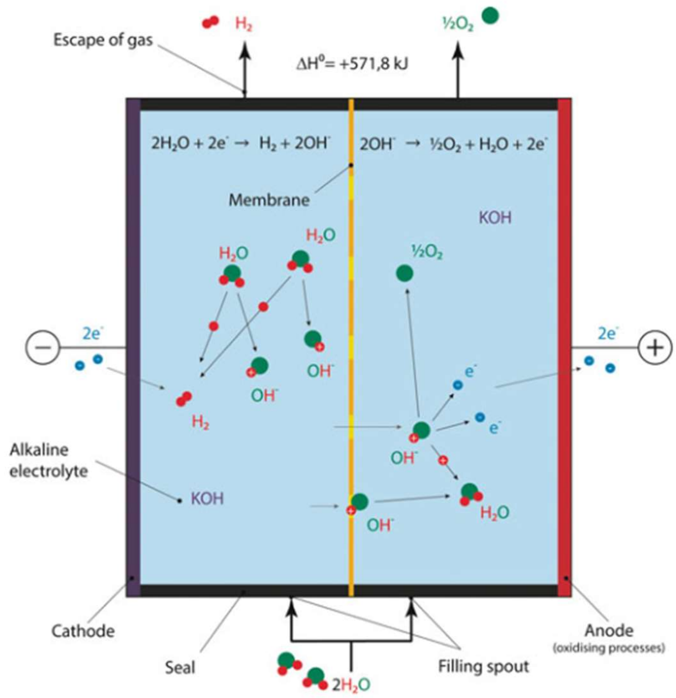


*Figure 3: Operating principle of AEL (Sterner and Stadler, 2019).*

The separation achieved by the ion conduction membrane results in an enhanced conductivity. The reduction in internal resistance within the cell is a consequence of the enhanced conductivity, which in turn results in an increase in efficiency. Figure 3 depicts the positioning of the porous cathode (black) and anode (red) in close proximity to the membrane on either side. In an ideal scenario, both electrodes are connected to a voltage that is equal to or greater than the voltage required for water decomposition which is approximately 1.23 V. In the cathode reaction water on the cathode-side split into atomic hydrogen ($H_2$) and hydroxide ions ($OH^-$), as can be seen in the following equation (1);

$$2H_2O\ (l) + 2e^- \rightarrow\ H_2\ (g) + 2OH^- \tag{1}$$

As a consequence of the cathode reaction, the generated protons react to atomic hydrogen molecules, which ascend and can subsequently be separated from the electrolyte. This allows for their departure from the electrolyzer, thereby enabling their use in a variety of applications. The remaining hydroxide ion molecules, diffuse through the porous membrane and react in the anode reaction. In the anode reaction hydroxide ions shed electrons and react to water and atomic hydrogen (2);

$$2OH^- \rightarrow \frac{1}{2}O_2(g) + H_2O(l) + 2e^- \tag{2}$$

Consequently, oxygen is produced as a result of the anode reaction and is separated from the electrolyte and is subsequently being released, as illustrated by the following equation (3);

$$H_2O(l) \rightarrow H_2(g) + \frac{1}{2}O_2(g) \tag{3}$$

Two electrons are required in each half-cell for a complete reaction. The required water is refilled by the water supply Figure 3 depicts a cell frame that encompasses the electrodes and isolates the electrodes from one another. The rise of gas bubbles ensures the circulation of the entire process; however, this is only effective when load is low. When the load is high, the electrolyzer must be actively recirculated, which necessitates the input of additional energy to sustain the process (Sterner and Stadler, 2019).

### *2.2.2. Electrolysis materials*

It is widely acknowledged that critical (CRMs) and strategic raw materials play a decisive role in the functioning of alkaline electrolyzer. With the projected expansion of the installed capacity in the coming years, a detailed examination of the utilized materials may prove invaluable. It is often miscounted that the assessment of environmental friendliness is solely contingent upon the reduction of greenhouse gas (GHG) emissions. In fact, a comprehensive evaluation of the employed materials is equally crucial. In this chapter, a closer look on the material demand of an alkaline electrolyzer is taken.

One significant benefit of an alkaline electrolyzer its capacity to utilize inexpensive non-platinum group metals (PGM), thereby circumventing the need for expensive and scarce noble materials. The anode (oxygen evolution reaction (OER)) of the alkaline electrolyzer is frequently composed of nickel (Ni), cobalt (Co) and iron (Fe), as these materials demonstrate optimal performance in an alkaline media. The most commonly utilized nonnoble electrode material is nickel, which has been employed for decades and served as a standard for anode materials in AEL (Eikeng et al., 2024b).

To increase the speed of the electrochemical reaction a catalyst coating is typically required. Commercially alkaline electrolyzer are using pure nickel or with nickel coated stainless steel (SS) (Eikeng et al., 2024b). Figure 4 illustrates the strategic and critical raw materials as well as non-CRMs materials which are required for an AEL.

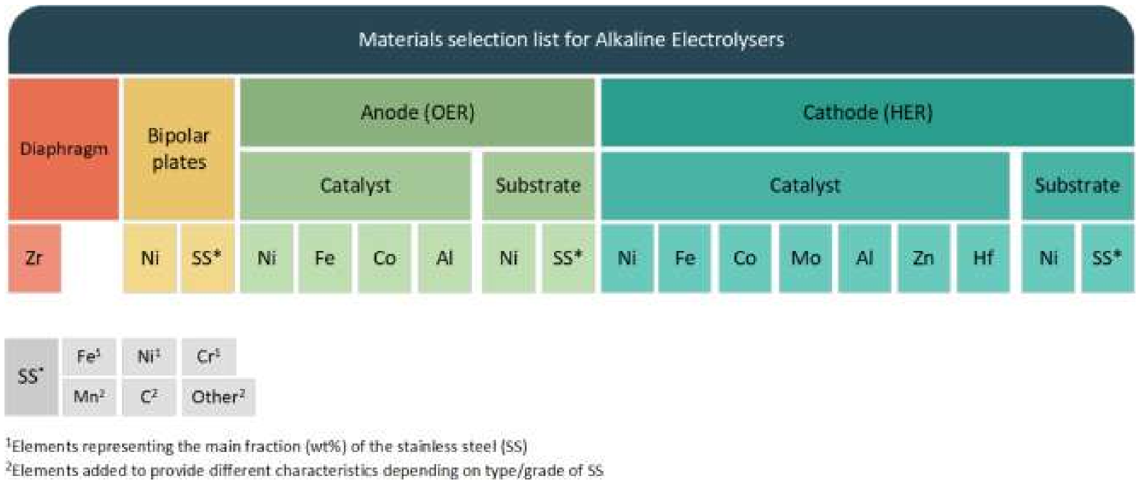


*Figure 4: Overview of viable materials selection for AEL (Eikeng et al., 2024b).*

## 2.3. Solar electricity generation technologies

In 2021, renewable energy sources accounted for a mere 1 % of the global hydrogen output production (IRENA, 2021). In 2019, fossil fuels constituted 80 % of the world total energy supply (IEA, 2021b). The electricity supply is also a crucial factor in the evaluation of electrolytic hydrogen production, as evidenced by the findings of LCA studies conducted by Burghardt (Burkhardt et al., 2016) and Koj (Koj et al., 2017). In order to produce environmentally friendly electrolytic hydrogen, a renewable energy supply, such as photovoltaics (PV) or concentrated solar power (CSP), is necessary.

### *2.3.1. Potential of solar energy*

Various studies have demonstrated that the global primary energy demand could theoretically be met in its entirety by solar energy. The quantity of solar energy that reaches the Earth is approximately 6,000 times higher than the annual primary energy requirements of the global population (Quaschning, 2020a). There are different technologies to use solar energy e.g. by producing solar electricity with photovoltaics (PV) or concentrated solar power (CSP).

### *2.3.2. Concentrated solar power (CSP)*

Concentrated solar power belongs as well as photovoltaics to the solar power technologies. In general CSP stand for a modern technology that utilize the heat harnessed from sunlight to generate renewable power (Yang, 2024). CSP plants are still in the nascent stages of market introduction. The potential of CSP to facilitate the climate-neutral transformation of the global energy market is frequently underestimated, despite the significant advantages they offer in terms of providing energy on a continuous basis, even in the absence of sunlight or with reduced sunlight due to the large storage capacities they possess (DLR, 2021a, 2021b).

In general, the solar thermal power plant uses mirrors to concentrate direct sunlight and to convert this sunlight into heat. The heat is stored in thermal storage tanks and can be used to produce steam to operate the turbines of the steam power process for electricity production. Concentrated solar power technology can be divided provided into four main technologies; linear Fresnel reflector (LFR), central receiver also known as solar tower plant, parabolic dish and parabolic trough, which can be also seen in Figure 5.

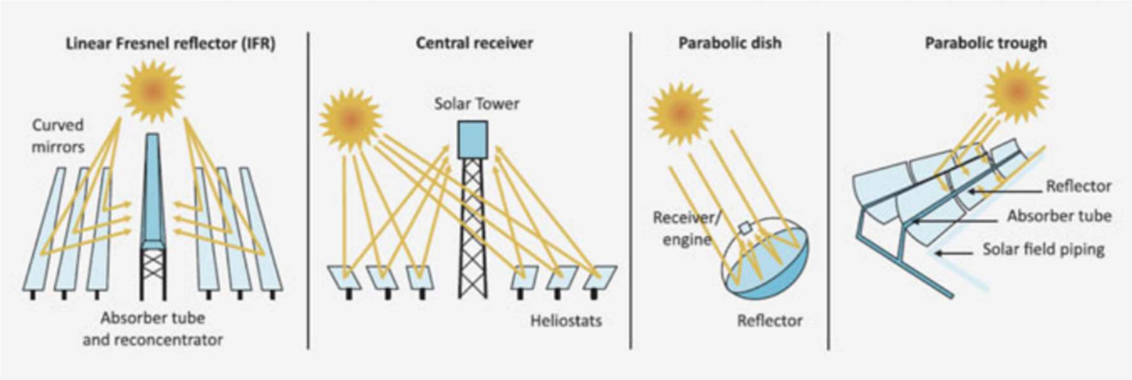


*Figure 5: Types of concentrated solar power systems (Yang, 2024).*

The general lifetime on an CSP plant is approximately 30 years (Gasa et al., 2022). In a solar tower plant, heliostats direct the solar radiation onto a central receiver mounted on a tower. The majority of the energy from the heat is absorbed by molten salt, which then transmits it into the thermal storage system. In the parabolic trough power plant, the heliostats track the sun uniaxially and focus the light, as can be seen in Figure 5 on an absorber tube aligned along the focal line. The absorber tube is comprised of two tubes separated from one another by a vacuum, which serves to reduce heat loss. The operation of the Fresnel reflector collectors is analogous to that of parabolic trough. The absorber tube of the linear Fresnel reflector collector is installed in a fixed position (DLR, 2021a).

Although parabolic trough power plants represent the most commercially implemented solar thermal power plant to date, this thesis will focus on solar tower power plants due to the availability of an LCA for this technology, which will be utilized in the alkaline electrolysis LCA as on part of the energy component.

### *2.3.3. Photovoltaics (PV)*

In 1839, the PV effect was first observed by the French physicist Alexandre-Edmond Becquerel. Bell Laboratories unveiled the inaugural practical silicon solar cell, in April 1954. The solar PV power industry is currently the fastest-growing energy industry in the world, driven by the pursuit of climate goals and government financial support in numerous countries (Yang, 2024). From 2013 to 2022, the cumulative installed capacity increased from 137 GW to 1185 GW, representing a growth rate of approximately 765 % (Melodie de l'Epine, 2023). At the present time, monocrystalline panels represent the most popular type of solar panel on the market. A significant advantage of PV over other solar power technologies is its high peak efficiency, which approaches 20 % (Rahaman and Iqbal, 2019). Additionally, PV has a relatively low cost for the production and operation. Compared to other renewable technologies as well as fossil fuels and nuclear power, PV has experienced a rapid decline in costs over the years However, it is important to note that PV cannot provide energy continuously, unlike CSP (Yang, 2024).

Worldwide the crystalline silicon (c-Si) PV plants have a share of production of 97 %, which makes it the most common PV technology (Fraunhofer ISE, 2024). The lifespan of monocrystalline solar cells is ranging from 25 to 30 years (Yang, 2024). In addition to monocrystalline solar cells, other types of solar cells exist, but they are not as prevalent. Therefore, crystalline silicon PV plants are selected for the LCA as the second component of the energy supply for the AEL.

### *2.3.4. CSP/PV hybrid solar-power plants*

In the recent years, there has been a notable increase in the interest surrounding the concept of hybrid solar PV and CSP power plant. The combination of these two solar power technologies offers significant advantages for the alkaline electrolyzer. Firstly, the concept of a solar PV/CSP hybrid plant is more economically viable for a high capacity factor than a CSP plant alone (Green et al., 2015).

In an alkaline electrolyzer, a constant energy supply is necessary to maintain the flow of the ions ($OH^-$) between the electrons. As previously outlined, PV is unable to provide a consistent energy supply due to its reliance on external factors such as weather, geographical location, and season variations (DLR, 2021b). The combination of both technologies offers a significant advantage in this field, as it is more cost-effective than CSP alone and can provide a continuous energy supply. The PV system will be used during daylight hours, contingent on favorable weather conditions. Conversely, the CSP system is utilized to store thermal energy, which can then be accessed during cloudy days or at night. Furthermore, an overall efficiency of over 40 % is achievable (Ju et al., 2017).

In conclusion, it can be stated that a combination of PV and CSP is a viable option in the context of the bachelor thesis, given that an alkaline electrolyzer requires a consistent renewable energy source to produce electrolytic hydrogen.

## 2.4. Methodology

Life Cycle Assessment (LCA) is a systematic method for evaluating the environmental impacts associated with all stages of a product's life cycle, depending on the set goal and scope of the LCA. The life cycle encompasses the extraction of raw materials, the manufacturing process, the utilization of the product, and the final disposal phase, which is also referred to as the end-of-life phase. According to the standards established by ISO 14040 and ISO 14044, the fundamental objective of LCA is to facilitate a comprehensive understanding and awareness of the environmental burdens associated with a product's life cycle, leading to the identification of areas requiring enhancement.

As illustrated in Figure 6 and delineated in the ISO 14040 and 14044 standards, the LCA is structured into four interconnected phases:

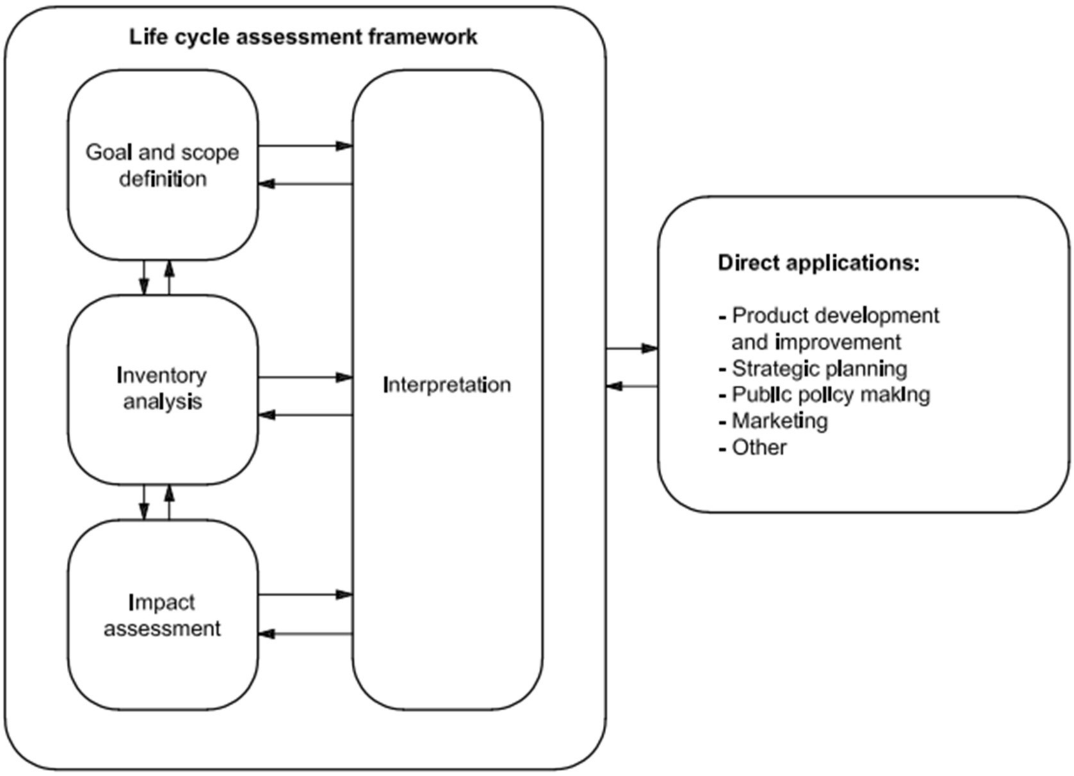


*Figure 6: Stages of an LCA (DIN EN ISO 14040).*

The goal and scope of the study delineate its purpose and establish the system boundaries. In this phase, the functional unit is also defined, providing a quantitative reference for comparisons. Furthermore, the assumptions necessary for the LCA to function are delineated. One particular note is the delineation of the system boundaries, which determines the life cycle stages deemed pertinent for the study. An LCA can be conducted using a cradle-to-grave, cradle-to-gate, or gate-to-gate approach. The cradle-to-grave approach encompasses the entire life cycle, from resource extraction to the disposal phase. The cradle-to-gate phase excludes the disposal phase from the analysis, incorporating all phases up to the operational phase. Conversely, the gate to gate analysis encompasses the phases from factory entry to exit gate, while excluding other phases such as the operational phase, thereby delineating a distinct analysis system boundary (Kawajiri and Kobayashi, 2022; Meng et al., 2017).

The inventory phase includes the life cycle inventory analysis (LCI), which means that the data which being used is named and listed, as well as the quantification of the inputs (e.g., energy, materials) and outputs (e.g., emissions, waste) throughout the life cycle stages.

In the life cycle assessment phase are the inventory results translated into potential environmental impact assessment categories such as the global warming potential (GWP). This phase includes classification, characterization, normalization and weighting of environmental impacts.

In the last phase the results are summarized and evaluated in line with the goal and scope. Also, a sensitivity analysis is done in the interpretation, ensures consistency and provides recommendations.

The execution of an LCA analysis can be facilitated by software such as LCA for Experts, OpenLCA, or Brightway. In this thesis, OpenLCA is employed due to its status as open-source software for life cycle and sustainability assessment, with capabilities for important databases, including the Ecoinvent database.

# 3. Life Cycle Assessment – Hydrogen Production

This chapter presents the LCA of electrolytic hydrogen production using solar electricity, focusing on alkaline electrolysis. The LCA for the electricity sources (CSP and PV) have already been created before and are customized depending on the system boundaries. The material list and functional unit of the CSP tower plant and the PV system can be found in the appendix. The system boundaries of the considered system can be seen in Figure 7.

## 3.1. Goal and scope

The following section delineates the goal and scope of the LCA for alkaline electrolysis, in accordance with the standards set forth in DIN EN ISO 14040 and DIN EN ISO 14044.

### *3.1.1. General*

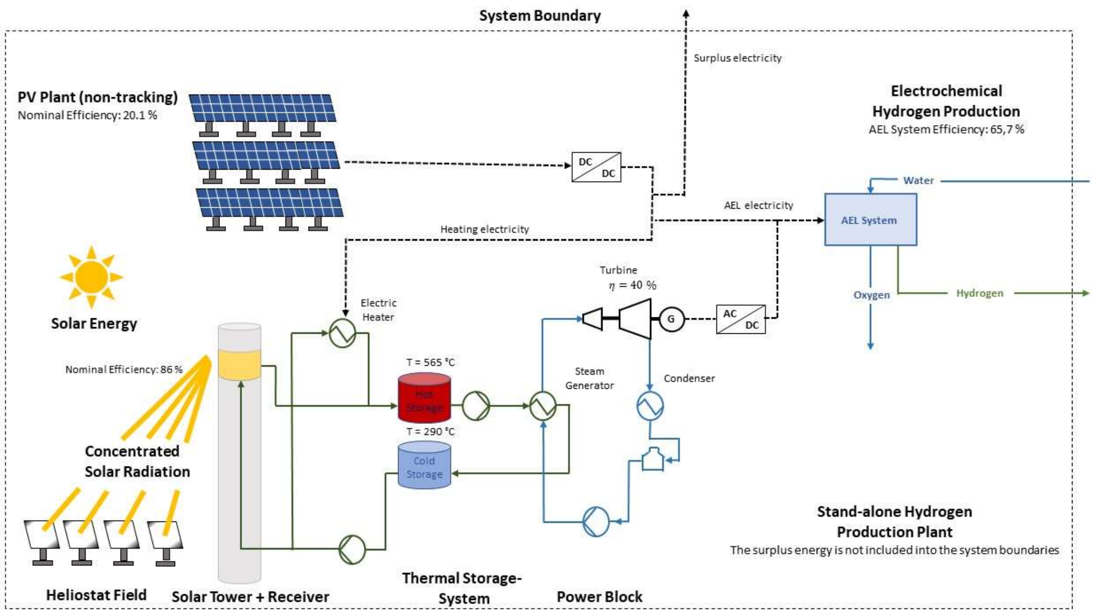


*Figure 7: System boundaries for the AEL LCA.*

As demonstrated in Figure 7 and previously outlined, this work investigates electrochemical hydrogen production powered by a CSP/PV hybrid energy source. The CSP/PV hybrid system was selected as an energy source for two primary reasons. First, it enables an increase in the operational hours of the electrolyzer, due to the integration of thermal storage, thereby enhancing the electrochemical hydrogen production rate. Furthermore, CSP/PV hybrid systems offers cost-effective relative to standalone CSP plants (Rosenstiel et al., 2021).

In addition to the selection of a solar energy source, the determination of an impact assessment method was imperative. ReCiPe (midpoint) H no long-term (LT) was selected due to the fact that the functional unit delineated in the subsequent chapter encompasses a 20-years' timeframe, which does not necessitate an extended period of observation. Furthermore, ReCiPe was selected due to its incorporation of the metal depletion potential, which is one of the investigate impact categories in this thesis. The decision to prioritize CSP as the primary energy source of the hybrid system was motivated by its demonstrated capacity to generate electricity with a reduced environmental impact compared to that of PV electricity, as indicated e.g. by lower greenhouse gas emissions (in g $CO_2$-eq) per kWh electricity produced. The overreaching objective was to construct a hydrogen production process that is as environmentally sustainable as possible.

The impact categories that were examined include: the potential of global warming (GWP), marine aquatic ecotoxicity (MAEDP), metal depletion (MDP) and terrestrial ecotoxicity (TAETP). The selection of these impact categories was driven by two key factors. These categories represent a substantial portion of the exceeded safe operating space of the planetary boundaries, necessitating improvement.

The findings of this thesis are part of a DLR internal research application and will contribute to a more nuanced understanding of the CSP/PV hybrid system's environmental impact as an energy source for the alkaline electrolyzer and the potential need for component substitution.

### 3.1.2. Function, functional unit and reference flows

The functional unit of the alkaline electrolysis is the production of 1 kg electrolytic hydrogen lifetime of 20 years with an annual operation of around 8000 $\frac{h}{a}$ depending on the location of the alkaline electrolysis is assumed. The determined electrolyzer full load hours for the investigated locations Spain, Saudi Arabia and Chile are $5\,278.67\ \frac{h}{a}$, $7\,144\ \frac{h}{a}$ and $8\,200\ \frac{h}{a}$. The combination of the solar electricity mixed with CSP and PV is also different between the locations depending on the direct normal irradiance (DNI) of the respective countries. The assumed lifetime of the stacks is 10 years which means the stacks are completely exchanged after 10 years. In Koj et al., an alkaline electrolyzer with a capacity of 6 MW and a hydrogen production rate of 118 $\frac{kg\ H_2}{h}$ (Koj et al., 2017) is described. This corresponds to approximately 3 $\frac{t\ H_2}{h}$ for the conducted and analyzed system. It is important to note that the total amount of hydrogen produced in different countries will vary due the differing full load hours. The specific calculations can be found in the appendix. The following Table 1 describes the technical characteristics of the alkaline electrolysis:

*Table 1: Technical characteristics - alkaline electrolyzer (IRENA, 2020b; Koj et al., 2017).*

| Parameter | Unit | Value |
|---|---|---|
| Electrolyte | - | Aqueous KOH solution (25 % w/w KOH) |
| Membrane type | - | Zirfon |
| Capacity | MW | 150 |
| Hydrogen production rate | $t\ H_2/h$ | 2.95 |
| Electricity to hydrogen efficiency | % | 65.7 |
| Hydrogen purity | % | 99.9 - 99.9998 |
| System lifetime | a | 20 |
| Stack lifetime | a | 10 |
| Stacks per AEL system | pcs | 100 |
| Annual operation | h/a | 8 000 |
| Operating pressure | bar | 33 |
| Operating temperature | °C | 85 |
| Hydrogen output temperature | °C | 40 |

### 3.1.3. System boundary

The subsequent analysis is a "cradle to gate" analysis, which signifies that the system boundaries will conclude with the generation of hydrogen. The end of life (EoL) phase and the question of where the produced hydrogen can be used are not included in the subsequent LCA. Cradle to gate was chosen as an system boundary because of the leak of available data how Zirfon membranes are going to be disposed (Koj et al., 2017). The production phase of the utilized materials is largely incorporated into the material processes of the Ecoinvent database, as they were not produced with the specific intention of being included in this analysis. In consideration of the 20-year lifetime of hydrogen production, maintenance and cleaning are incorporated into the analysis. For the completeness of the analysis, the transportation should actually be considered as well. However, due to the lack of available data for the considered countries was assumed that the environmental impact of transportation can be neglected. Therefore, it was chosen to do not modify the transportation distances of the raw material to their production countries.

Figure 8 illustrates the general process flow diagram, which is applicable to all three locations during the operational phase. The direct normal irradiation, as well as the hydrogen production rate and net energy production, undergo changes.

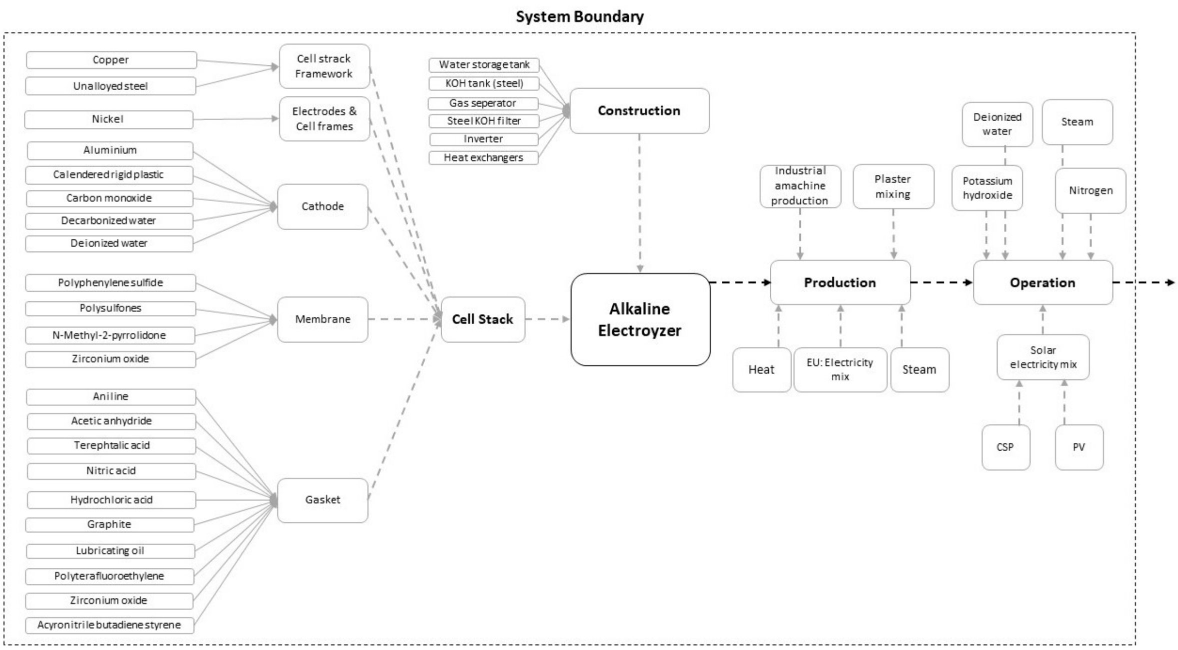


*Figure 8: System flow diagram of electrochemical hydrogen production.*

### *3.1.4. Cut-off criteria and allocation procedure*

The AEL, CSP and PV systems and its components are not manufactured with the production of by-products. Moreover, in accordance with the recommendations set forth in DIN EN ISO 14044, no allocations will be employed in the subsequent LCA. However, it should be noted that in some of the processes used, for example in the electrical wiring process, some allocations were modeled in the Ecoinvent v3.10 processes.

In consideration of the established cut-off criteria, the adhesive utilized for the attachment of different components such as the glass of the heliostats are not taken under account because the used adhesives have a share of less than 5 % in the respective product systems. The transportation processes of the different materials are also cut off, as their impact on the greenhouse gas (GHG) emissions and their impact on water will be low.

### *3.1.5. Methods for impact assessment and evaluation*

The impact assessment and evaluation are conducted in accordance with the ReCiPe 2016 v1.03, midpoint (H) no LT method. In order to create a target impact assessment, it is necessary to employ specialized methods which are divided into two optional categories. The mandatory methods include classification and characterization.

The classification stage involves the assignment of lifecycle inventory results to impact categories. The characterization stage involves the quantification of the contribution to the respective impact categories and the calculation of the impact indicator values. The optional methods include standardization and evaluation. In the evaluation phase, the impact potentials are assigned a weighting, ranking, or ordering.

The impact categories subjected to analysis can be seen in Table 2. However, there are numerous additional impact categories that can be analyzed, depending on the specific goal and scope of the LCA.

*Table 2: Overview of the chosen impact categories for the LCA.*

| Impact category | Short form | Unit |
|---|---|---|
| Global warming potential no LT | GWP | $\frac{kg\ CO_2 - Eq}{kg\ H_2}$ |
| Terrestrial ecotoxicity potential no LT | TAETP | $\frac{kg\ 1.4\ DCB - Eq}{kg\ H_2}$ |
| Marine aquatic ecotoxicity potential no LT | MAETP | $\frac{kg\ 1.4\ DCB - Eq}{kg\ H_2}$ |
| Metal depletion potential no LT | MDP | $\frac{kg\ Cu - Eq}{kg\ H_2}$ |

### *3.1.6. Data quality requirements and limitations*

For the conducted alkaline electrolyzer LCA generic data from the Ecoinvent v3.10 database, as well as data from Koj et. al. and also data from Akhtar et. al. was chosen. For the CSP and PV LCA also generic data from the Ecoinvent v3.10 database was used. Furthermore, for the CSP materials, papers from Gasa et al. (Gasa et al., 2021) as well as data from the DLR tool Greenius was used. For the PV LCA a material list from IEA PVPS-Task 12 and other data from the Umweltbundesamt (UBA) (IEA PVPS Task 12, 2020; Umweltbundesamt, 2021) was used.

The data requirements and limitations of this LCA are as follows: The data employed should align temporally and geographically with the presumed locations and timeframes of the systems under investigation. The processes employed should align with the characteristics of the respective material. It is not possible to meet the requirements for full due to the limited availability of data. A pedigree matrix is used for the purpose of evaluating the data.

For the processes utilized from the Ecoinvent v3.10 database is no information provided regarding the quality of the data. Nevertheless, the companies, research projects, documents and papers from which the data was derived are described. It is striking that, most of the used processes are created on data which is significantly older than the time period considered. For example, the dataset for the three-conductor cable is based on information from 2007 to 2011, which has a deterimental effect on the overall quality of the data. However, it should be noted that the Ecoinvent database used is one of the most recent versions of the Ecoinvent v3.10 databases. On November, $19^{th}$ a new version v11 of the Ecoinvent database was released.

Furthermore, the assumptions that were made introduce an element of uncertainty, particularly with regard to the geographical location of the processes. A country-specific process could be developed for a few processes, for example, for the energy mix utilized in the production process. The majority of processes were global processes with not a specific geographical process.

In general, the assumptions are found to be in moderate agreement with the process data.

### *3.1.7. Assumptions*

In the absence of disassembly of the product under consideration of the LCA, assumptions are inevitable given the lack of access to the data necessary for a comprehensive understanding of the process. Furthermore, the confidentiality obligations of the various companies with their different production routes and sites, along with the origin of the processed raw materials, necessitating additional assumptions to be made on that basis.

Given the unavailability of data pertaining to the production phase of the utilized components for the alkaline electrolyzer, CSP tower plant and the PV system, only the data already included in the Ecoinvent 3.10 cutoff database for the aforementioned processes could be utilized. The assumption was made, that most of the chosen raw materials were produced in China (Statista, 2024). Accordingly, the processes are adapted to align with the specific country-level processes wherever feasible.

As already described the transportation processes of the materials was not modelled, because of the lack of available data and the limitation of time. The assumption was made that these discussed will not have a decisive influence on the results of the conducted LCA.

According to the used materials list, for the alkaline electrolyzer the plastic polytetrafluoroethylene also known as Teflon is part of the gasket. Unfortunately, the used Ecoinvent v3.10 cutoff database does not include the polymerization part of this specific. Due to the lack of the polytetrafluoroethylene, tetrafluoroethylene was chosen which leads to uncertainties. In addition, the material list for the cathode includes calendared plastic. Since there is no specific data which calendared rigid plastic was used, the assumption was made that it is polyvinylchloride (PVC). Because of the lack of available data and the limitation of time the heat exchangers which are part of the construction of the alkaline electrolyzer was not modeled. The assumption was made, that the heat exchanger does not affect the results significantly.

Moreover, the assumption was made that the lifetime of the alkaline electrolysis will be 20 years. This lifetime was chosen because literature of LCAs of alkaline electrolyzer mostly assumed a lifetime of 20 years (Gerloff, 2021; Koj et al., 2017; Krishnan et al., 2024; Zhao et al., 2020). With the assumption of 20 years a validation of the literature results easier.

Gemma Gasa et al. used in their LCA for the CSP plant the material "silicone-based coating" from the Ecoinvent v3.6 database (Gasa et al., 2021). Unfortunately, this process is not part of the Ecoinvent database v.3.10 which is why silicone product was used instead.

In terms of the operation phase, the assumption was made that the CSP tower plant will have almost the same emissions with a thermal energy storage (TES) of 14 h instead of a TES of 17.5 h. This assumption is based on a paper which described the influence of the storage hours on the emissions of the CSP tower plant. The results showed that the emissions do not change increasingly per kilowatt hour between 9 h and 17.5 h (Gasa et al., 2022).

## 3.2. Life cycle inventory analysis

### *3.2.1. Data collection*

For the inventory analysis of the alkaline electrolyzer, data will be used from two different papers. The following materialist (Table 3) is based on data provided in the year 2017 and 2021 (Akhtar et al., 2021; Koj et al., 2017).

*Table 3: Manufacture inventory - alkaline electrolyzer (Akhtar et al., 2021; Koj et al., 2017).*

| Parameter | Unit | Value | Component |
|---|---|---|---|
| **Construction** | | | |
| Water storage tank | l | 7 800 | **Construction** |
| KOH tank (steel) | kg | 1 000 | |
| Gas separator | kg | 1 242.5 | |
| Heat exchangers | kg | 975 | |
| Inverter | MW | 0.625 | |
| steel KOH filter | kg | 36.25 | |
| **Cell Stack Framework** | | | |
| Copper | t | 0.5 | **Cell stack frameworks** |
| Unalloyed steel | t | 50 | **Cell frames** |
| **Cells** | | | |
| Nickel | t | 4.75 | **Electrodes and cell frames** |
| Aluminium | kg | 112.5 | **Cathode** |
| Calendered rigid plastic | kg | 195 | |
| Carbon monoxide | kg | 37.5 | |
| Decarbonized water | t | 2.75 | |
| Deionized water | t | 21.5 | |
| Polyphenylene sulfide | kg | 85 | **Membrane** |
| Polysulfones | kg | 65 | |
| N-Methyl-2-pyrrolidone | t | 0.325 | |
| Zirconium oxide | t | 0.275 | |
| Aniline | kg | 12.25 | **Gasket** |
| Acetic anhydride | kg | 13.5 | |
| Terephthalic acid | kg | 22 | |

| | | | |
|---|---|---|---|
| Nitric acid | kg | 8.25 | |
| Hydrochloric acid | kg | 32.5 | |
| Graphite | kg | 107.5 | |
| Lubricating oil | kg | 0.12 | |
| Polytetrafluoroethylene | kg | 19.5 | |
| Acrylonitrile butadiene styrene | kg | 40 | |
| **Energy** | | | |
| Electricity | GJ | 9 | **Energy** |
| Heat | GJ | 22 | |
| Steam | MJ | 175 | |
| Industrial machine production | kg | 0.04 | |
| Plaster mixing | kg | 195 | |

The materials shown in the Table 3 have been adapted to align with the defined system boundaries. In the paper from Koj et al., the alkaline electrolyzer system was defined for a capacity of 6 MW (Koj et al., 2017). Consequently, all the materials presented in Table 3 were scaled up linearly to accommodate the 150 MW system. Table 4 shows the inventory list for the analyzed alkaline electrolyzer.

*Table 4: Operation inventory list - alkaline electrolyzer (Akhtar et al., 2021; Koj et al., 2017).*

| Parameter | Unit | Value | Component |
|---|---|---|---|
| Electricity | $\frac{MJ}{kg\ H_2}$ | 180 | **Production** |
| Deionized water | $\frac{kg}{kg\ H_2}$ | 10 | |
| Nitrogen | $\frac{g}{kg\ H_2}$ | 0.29 | |
| Potassium hydroxide | $\frac{g}{kg\ H_2}$ | 1.9 | |
| Steam | $\frac{kg}{kg\ H_2}$ | 0.11 | |

### 3.2.2. Input

#### 3.2.2.1. General resource consumption

Input is divided into five subcategories under the resource category, as delineated by ISO 14040 and 14044. These subcategories, which belong to the upper category resource, encompass the following: biotic, in air, in soil, in water, and in land. Collectively, these subcategories generally describe resource consumption from different sources within the input. The biotic subcategory specifically refers to resources that involve living organisms and the processes and conditions they inhabit. Biotic environmental factors, which include plants, animals, bacteria, and fungi determine the structure of an ecosystem, thereby influencing the material cycle and energy flows within it. Another impact category is “air”, which describes the consumption of resources from the atmosphere. The category “ground” encompasses resources extracted from the ground, such as rare earths. The “water” category encompasses rivers and their influence on water resources, while the ”land” category addresses the extent of land use.

The overall resource consumption within the system boundaries is influenced by the annual yield of the installation countries, resulting in variations across these countries. Additionally, the resource consumption is contingent on the specific electricity mix, which significantly impacts the resource consumption of the entire system under consideration.

#### 3.2.2.2. Relevant processes with regard to resource consumption

The resource consumption is at its greatest for the electrochemical hydrogen produced in Spain, compared with the other conducted sites. The lowest resource consumption was observed in Chile, attributable to the highest solar irradiation levels in that region. As a result, Chile has the highest net electricity production which consequently enables the production of the greatest amount of electrochemical hydrogen of the three sites studied.

The substantially elevated resource consumption observed in Spain can be attributed to the comparatively low DNI. However, it is noteworthy that from a DNI higher than 2 100 $\frac{kWh}{m^2\,a}$, resource consumption exhibits minimal fluctuations between the installation countries. It is also noteworthy that the resource consumption at the location in Chile, which has a DNI of approximately of 2 900 $\frac{kWh}{m^2\,a}$ (Benitez et al., 2019), and Saudi Arabia, with a DNI of around 2 600 $\frac{kWh}{m^2\ a}$ (Dr. Christoph Schillings, 2010) is 4.10 $\frac{kg}{kg\ H_2}$ lower. The DNI of Almeria is approximately 2 100 $\frac{kWh}{m^2\ a}$, indicating that the difference in resource consumption between the two sites is approximately equivalent. However, the discrepancy in resource consumption between Spain and Saudi Arabia is approximately 9.20 $\frac{kg}{kg\ H_2}$. Consequently, it can be deduced that resource consumption will be significantly lower with a DNI higher than 2 100 $\frac{kWh}{m^2\ a}$.

Regarding the resource consumption, the most significant utilization is observed in the categories of "in water" and "in ground". The resource consumption of these categories varies between the countries, contingent on the DNI. However, in all locations examined, the "in water" category accounts for approximately 70 % of the resource consumption, while the "in ground" category accounts for approximately 25 %. The remaining input categories exhibit a substantially diminished influence on the resource consumption. The categories "biotic" and "in air" account for approximately 2 to 2.5 % of the input resource consumption, while the categories "land" and "fossil well" account for less than 1 %.

The impact of the "in water" input category is probably linked to the fossil energy sources of the electricity production processes which requires water for the operation of the steam power cycle.

Gangue and gravel have the highest resource consumption in the category "in ground" also relevant are hard coal, calcite and iron. Gangue is a material that has no commercial value and is found in close proximity to or in association with a desired product in a mining area such as an open pit mine. This byproduct can also have significant environmental impact, as oxidation with pyrite can lead to soil acidification (G. J. M. W. ARKESTEYN, 1980). The substantial consumption of resources is attributable to the extraction of raw materials utilized in the alkaline electrolyzer as well as in the CSP tower plant and the PV system. The mining of copper or aluminum can result in the production of gangue or gravel, thereby contributing to the substantial resource consumption associated with the extraction of raw materials.

In essence, the input or resource consumption is contingent upon the raw materials necessary for the current CSP tower plant. Consequently, it can be deduced that a reduction in raw material consumption would also result in a decrease in consumption for the existing alkaline electrolyzer, the CSP tower plant and the PV system.

### *3.2.3. Output*

#### *3.2.3.1. General output*

According to ISO standards 14040 and 14044, the term "output" is defined as the product, material, or energy flow emitted by a process module. The output of the electrochemical hydrogen production is divided into three categories: emission to air, emission to soil, and emission to water. The "emissions to air" category encompass emissions of air pollutants such as volatile organic compounds (VOCs), particles, and pesticides. The emissions to water category encompass emissions to both fresh water and saltwater bodies. These encompass both organic and inorganic emissions, along with emitted heavy metals. The final output category, encompasses emissions to soil. Similar to water emissions, these are organic and inorganic emissions. Additionally, substances that can be introduced into the soil used for agriculture are also considered.

#### *3.2.3.2. Relevant processes in terms of emissions*

As with resource consumption, the emissions from the output of the electrochemical hydrogen production are highest at the installation site in Spain. This effect can also be attributed to the significantly lower annual electricity yield compared to the installation countries Saudi Arabia and Chile, which have a higher hydrogen production rate.

The total emission in Spain are almost two times higher than for the electrochemical hydrogen produced in Saudi Arabia. For Chile the emissions are lower than for the other two locations. As with resource consumption, a clear distinction emerges in emission levels when comparing sites with a DNI below 2100 $\frac{kWh}{m^2\ a}$ to those with a DNI above 2100 $\frac{kWh}{m^2\ a}$. A notable correlation is apparent between total emissions and the DNI of the respective installation countries.

An analysis of the three installations sites reveals that "emissions to air" are the most significant category, followed by "emissions to water". Conversely, "emissions to soil" have the least influence on total emissions. The "emissions to air" category accounts approximately 80 % of total emissions, while "emissions to water" contribute significantly, with around 16 % of total emissions originating from this category. Consequently, it is concluded that "emissions to soil" have minimal influence on total emissions, with a share of less than one percent.

With regard to the "emissions to air", Radon-222 accounts for over 76 % of total emissions, with noble gases contributing approximately 19 %. Radon, a naturally occurring radioactive noble gas, is primary contributing to these emissions. The significant presence of radon in air emissions can be attributed primarily to anthropogenic activities, such as mining, the use of coal, or shale gas, which have been shown to increase the radon content (Wysocka et al., 2022). The substantial emissions can be linked to the extraction of raw materials for the components of the electrochemical hydrogen (alkaline electrolyzer, CSP tower plant as well as the PV plant). Consequently, it can be deduced that the extraction of raw materials exerts a substantial influence not only on resource consumption but also on the aggregate emissions of the plant under investigation.

The emissions into the water are primarily attributable to two primary factors. Firstly, the water utilized in the steam power process of the investigated plant is one of the primary contributors to the emissions. Secondly, the water employed for the cleaning of the heliostats and PV modules is also a significant contributor to the emissions. The cleaning of the modules and heliostats are essential to ensure their continued desired efficiency. The emissions into water can also be accounted for the mining of the raw materials as well as for the fossil energy source (hard coal) used for the production of the majority of the materials.

### *3.2.4. Data validation*

The used data sets from Ecoinvent v3.10 were not subjected to evaluation within the documentation. However, it is feasible to ascertain the source or origin of the data and the composition of a data set employed. Given the possibility to accessing the documentation and tracing the origin of the data sets used, a moderate to high level of data validation can be achieved.

The datasets, which were utilized from Koj et al. (Koj et al., 2015; Koj et al., 2017), exhibit an exemplary data quality, as the employed data is derived from primary sources and literature. Subsequently the findings were subjected to discourse and validation through the lens of LCA of AEL from extant literature. The efficiencies used for the individual components of the current alkaline electrolyzer and also for the CSP tower plant and the PV system show a very good data quality, as these were calculated with the help of Greenius (an DLR internal program for the calculation of the energy demand of different locations, as well for the design of the CSP tower plant, the program includes also detailed weather data for the different locations). The data quality of efficiency of the systems utilized are also very good because they were validated in the used papers (Koj et al., 2015; Koj et al., 2017).

Furthermore, it should be emphasized that the CSP DNI for the respective locations corresponds to a very good data quality, as it is based on averaged weather data from Meteonorm, which has averaged the DNI over climate periods (1996 - 2015), so that for example for Chile the El Niño was also included in the DNI determination. For the determination of the full load hours of the PV system a working paper from the HYPAT project from Fraunhofer institute was used (Christoph Kleinschmitt et al., 2022). It, can be described with good data quality, but the determined full load hours are subject to certain uncertainties due to the inaccuracy of the readings.

As a consequence of the absence of country-specific procedures in Ecoinvent v3.10, global processes had to be employed in certain instances, which has an adverse effect on the quality of the data.

## 3.3. Life cycle impact assessment

The subsequent section utilizes a set of four impact categories to evaluate the extent to which the hydrogen production process, conducted mainly of AEL as well as the CSP/PV hybrid plant, exerts influence over the respective categories throughout the plant's overall life cycle. A comparative analysis was conducted on the various installation locations, including Spain, Saudi Arabia and Chile.

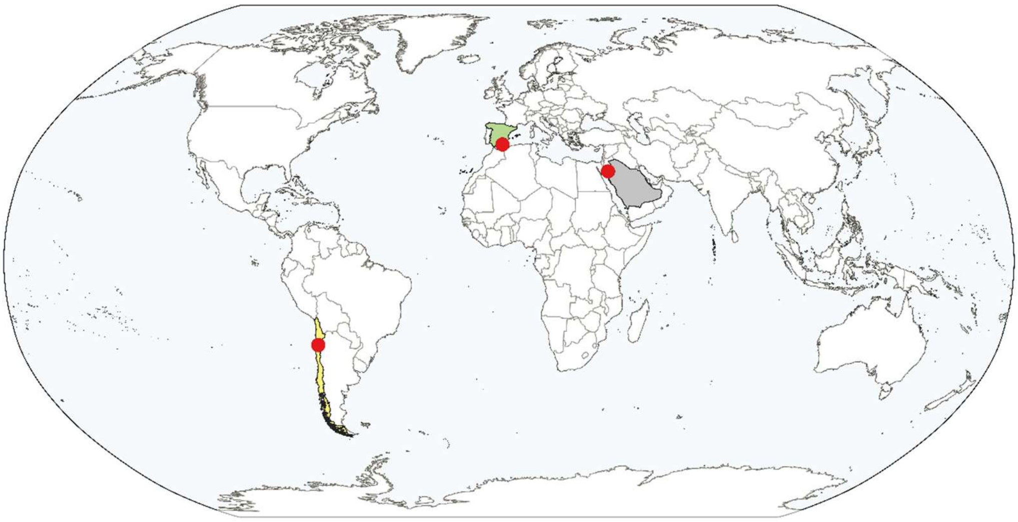

*Figure 9: AEL installation countries.*

It can be posited that the four distinct impact categories - climate change (no long-term [LT]), also known as global warming potential (GWP); marine aquatic ecotoxicity potential, terrestrial ecotoxicity potential (TAETP) and material resources (metal/minerals), or also named metal depletion potential (MDP)- will exhibit disparate hotspots of utilized components. The environmental impact of the installations is contingent on the net electricity yield at each side.

### *3.3.1. Global warming potential (GWP/ climate change no LT)*

The term "climate change" or "global warming potential" is used to describe the emission of the greenhouse gases and the associated effects on the Earth's radiation budget. The various gases are specified in $CO_2$-equivalents. Accordingly, the climate change potential serves to indicate the potential of a given substance to contribute to the heating of the air layers situated in proximity to the ground (Forschungsstelle für Energiewirtschaft e. V., 2024).

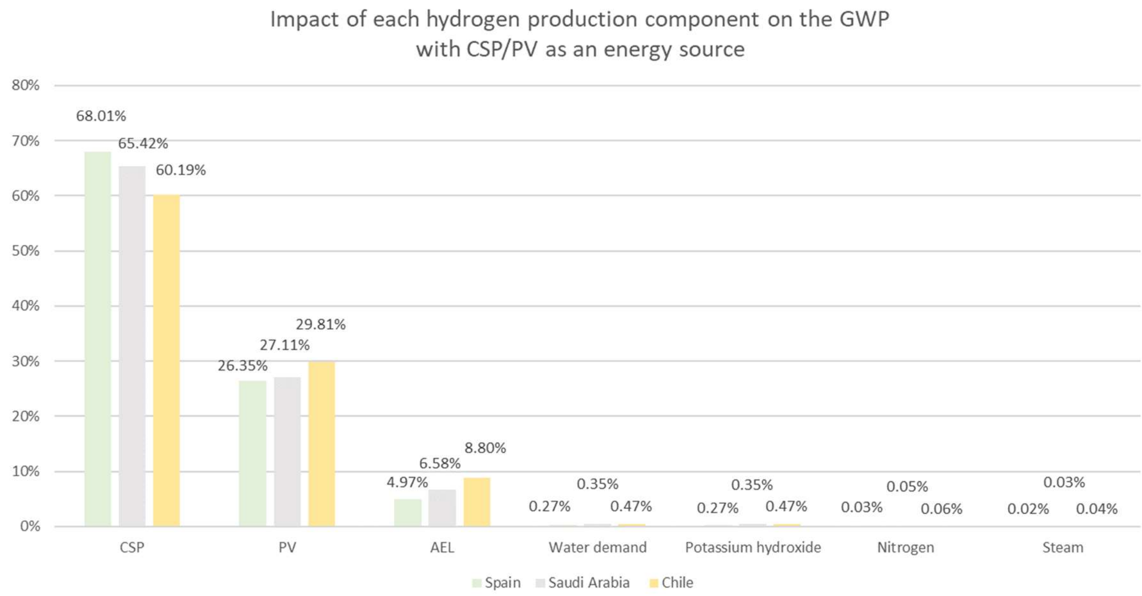


*Figure 10: Impact of each $H_2$ production component on the GWP powered by the CSP/PV hybrid system.*

Figure 10 presents a comparative analysis of the contribution of various renewable energy technologies and materials in Spain, Saudi Arabia, and Chile. Key variables include CSP, PV, AEL, water demand, potassium hydroxide, nitrogen and steam.

As illustrated in Figure 10, contributions from electricity generation are the primary factor influencing the outcomes. Consequently, CSP emerges as the predominant technology across all three nations, with Spain leading at the forefront 68.01 %, closely followed by Saudi Arabia (65.42 %), and Chile (60.19 %). PV technology exhibits a substantial presence, with contributions, ranging from 26.35 % in Spain to 29.81 % in Chile. Saudi Arabia exhibits a median value of 27.11 %. The alkaline electrolyzer has relatively negligible contributions, with the highest percentage recorded in Saudi-Arabia (8.80 %), followed by Chile (6.58 %) and Spain (4.97 %).

Figure 10 illustrates that the material and resource demand for the operation phase are minimal across all countries, except for the water demand. A similar trend is exhibited by potassium hydroxide (KOH). Furthermore, nitrogen and steam demonstrate a negligible contribution across all countries, with percentages consistently below 0.1 %.

It is interesting to note that the CSP dominates the impact on the GWP. This is not related to the materials being used, but mainly on the fact that the CSP plant provides a higher share of the electricity for hydrogen production. As the CSP plant is therefore larger than the PV plant more materials are also required for its construction. Chile has the highest impact on the AEL compared to the other locations, reflecting a strategic focus in this technology. Water and material demand remain low across all regions, indicating resource efficiency in these processes. Given the dominance of CSP in terms of greenhouse gas emissions, a pie-chart diagram (Figure 11) was developed to illustrate the materials that affect the CSP tower system. This diagram illustrates the materials that exert the most significant influence on the CSP technology impact on the GWP.

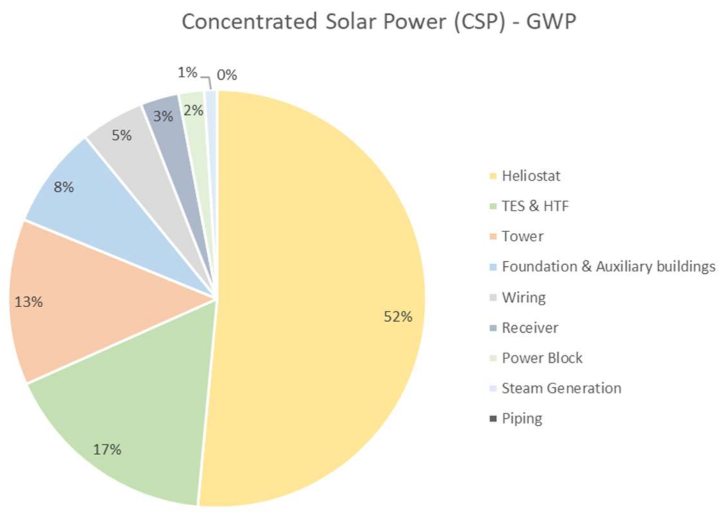


*Figure 11: Influence of the CSP tower plant on GWP for the electrochemical hydrogen production powered by the CSP/PV hybrid system.*

The most significant contributor is the heliostat segment, accounting for 51.87 %. A more detailed examination of the heliostats reveals that the utilization of steel (unalloyed and low-alloyed) and flat glass has the most significant impact on greenhouse gas emissions. The elevated emissions of steel can be attributed to the substantial amount of energy required in the steel production process (Lei et al., 2023). This energy is, primarily derived from fossil fuels, with the specific energy source varying depending on the country of production. China is the predominant producer of steel (Statista, 2024). In addition, it is imperative to consider greenhouse gas emissions associated with glass production. It is estimated that the emissions associated with the utilized flat glass can be attributed to the energy (48 %) required for glass production (Hertwich, 2021).

The PV system constitutes the second most significant contributor. The PV module exerts a substantial influence on the PV system's emissions, accounting for nearly 90 % of the total emissions. The generation of electricity and the composition of the wafer have the greatest impact on the greenhouse gas emissions of the module. As illustrated in Figure 12, the components of the PV module that significantly impact its emissions include the following: Of these components, the electricity utilized during the module's manufacturing process exerts the greatest influence on its emissions. This considerable impact can be attributed to the predominant use of hard coal, a primary fossil fuel in China's electricity generation, as a source of energy. The silicon production process is the second most significant contributor to these emissions, with the wafer being the primary source of impact.

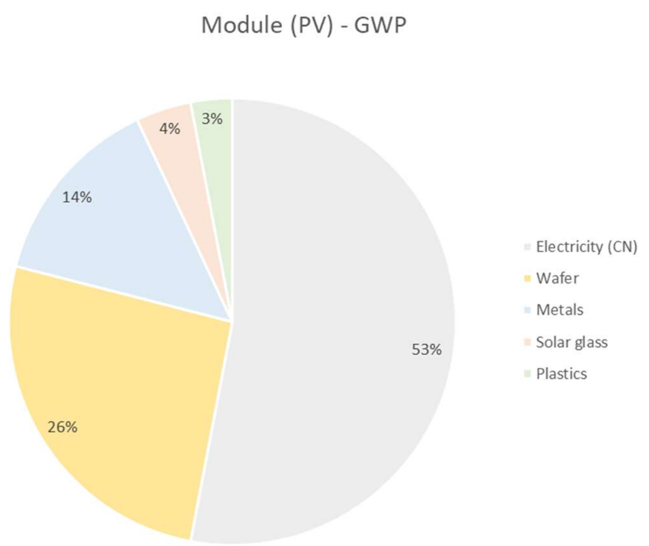


*Figure 12: Influence of the PV module on GWP for the electrochemical hydrogen production powered by the CSP/PV hybrid system.*

A thorough examination of the cell stack (AEL) reveals that the cell stack framework exerts the most significant impact on greenhouse gas emissions. The primary contributor is unalloyed steel. The influence of unalloyed steel on the GWP is affected by the huge energy demand which is needed for the steel production process. As analyzed and written before, the huge share of fossil fuels, mainly the hard coal, are the main contributor on the emissions of steel.

### *3.3.2. Marine ecotoxicity potential (MAETP)*

The marine aquatic ecotoxicity potential is an indicator for environmental toxicity and refers specifically to marine organisms (organisms that have their main habitat in sea-water). It describes the input of toxic substances such as copper into the marine habitat and is expressed in dichlorobenzene (DCB) equivalents (Acero et al., 2015).

As illustrated in Figure 13, the influence of the hydrogen production from the utilized locations on water ecotoxicity is described. The energy contributions exert a predominant influence on the MAETP. The analysis indicated that CSP maintains its dominant status across all locations, exhibiting a range of influence percentages between 72.47 % and 82.02 %, depending on the specific country under consideration. The alkaline electrolyzer also demonstrates a substantial impact on the MAETP. Chile exhibits the highest percentage of influence, reaching nearly 20 %, followed by Saudi Arabia with approximately 15 % to 11 % in Chile.

Across all countries under consideration, the influence of water demand and potassium hydroxide (KOH) is minimal, representing less than 0.1 % of the total MAETP. It is noteworthy that the utilized renewable energy system (CSP/PV hybrid plant) has the greatest impact on water ecotoxicity. The observed influence was hypothesized to be attributable to the water electrolysis process. During the hydrogen production process, the water utilized in electrolysis is often partially contaminated, potentially leading to leaching events. These leaching events, in conjunction with the water usage, have the potential to exert a substantial influence on the water ecotoxicity of the entire hydrogen production process. However, it has been observed that the influence during the production phase of the renewable energy materials used is more decisive.

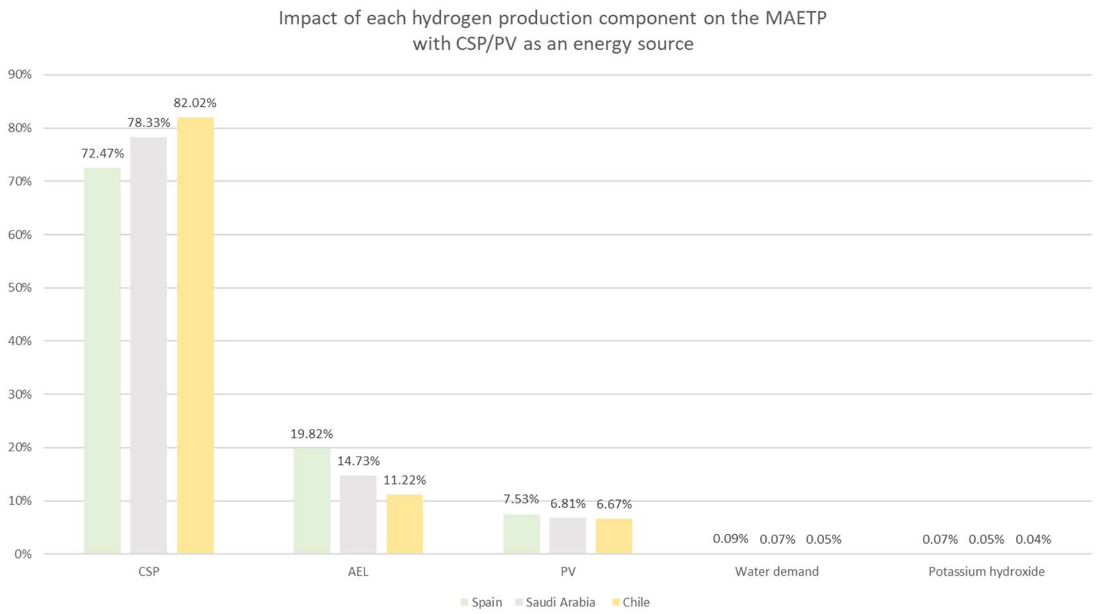


*Figure 13: Impact of each hydrogen production component on the MAETP powered by the CSP/PV hybrid system.*

As illustrated in Figure 14, the components of the CSP tower plant and the PV module exhibit a significant impact on the system's MAETP. The heliostats are the dominant contributors of the CSP tower plant. A detailed examination of the heliostat production process reveals that steel (low-alloyed and unalloyed) has a predominant impact on the ecotoxicity of the marine aquatic environment accounting for approximately around 96 % of the total effect. The production process of steel, particularly pig iron production, has a significant impact on the ecotoxicity of the marine aquatic environment. The production process of steel has been identified as a significant source of concern for the integrity of the water environment (Olmez et al., 2016).

The remaining 4 % are attributed to the deterioration of copper (CU) from the electronics, a prevalent heavy metal in aquatic systems, originating from both natural and anthropogenic sources. Natural sources include volcanic activity, geological deposits, weathering, and erosion of rocks and soil. Anthropogenic sources include mining, agriculture, sludge from public sewage treatment plants, metal and electrical industries, and the use of pesticides. The copper observed in this study is likely derived from sludge or the metal and electrical industry. Even at low concentrations, dissolved copper can prove toxic to a multitude of aquatic organisms. Following the release of copper into water, the dissolved copper can be transported in surface water in either its free form or that of compounds. Ultimately, it can be deposited in the sediments of rivers, lakes, and estuaries, or it can become bound to particles that are suspended in the water. While copper demonstrates a notable affinity for suspended solids and sediments, evidence suggests that some water-soluble copper compounds may also infiltrate groundwater (NDR, 2022; Smriti et al., 2023).

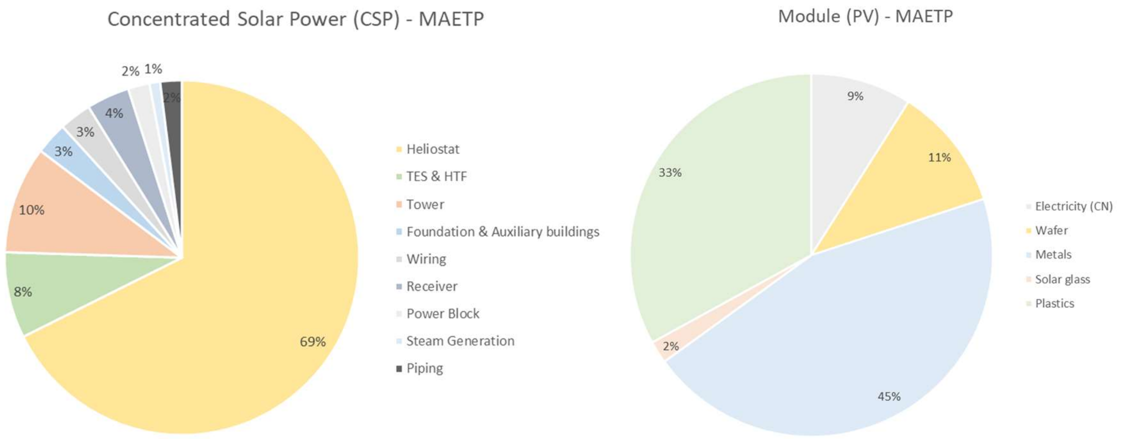


*Figure 14: Influence of the CSP and PV module on MAETP for the electrochemical hydrogen production powered by the CSP/PV hybrid system.*

As illustrated in Figure 14, the utilization of diverse materials in PV modules significantly impacts water ecotoxicity. Metals comprise the predominant proportion of the pie chart, accounting for 45.07 % of the total distribution. Among the metals, aluminum alloy, copper and silver exhibit the most significant impact on the DCB-equivalents. The second largest impact on the water ecotoxicity is attributed to the wafer, specifically silicon. The significant impact of copper is attributed to the intensive production process, which requires substantial water usage and exerts a substantial influence on the utilized water. The cell stack has the highest impact on the DCB-equivalents, with an almost 97 % share. This impact is attributed to more than 99 % of the cell stack framework. The substantial influence of the cell stack framework is attributable to the steel production process. The process exerts a predominant influence on the cell stack framework.

### *3.3.3. Metal depletion potential (MDP)*

The material resources, namely metals and minerals or also metal depletion potential (MDP) is a part of the abiotic depletion potential (ADP), which can be further subdivided into two categories: metal and fossil depletion. The MDP is contingent upon the quantity of metal and mineral resources, as well as the extraction rate. The measurement of MDP is expressed in kilogram copper-equivalents (kg Cu-Eq) (Acero et al., 2015).

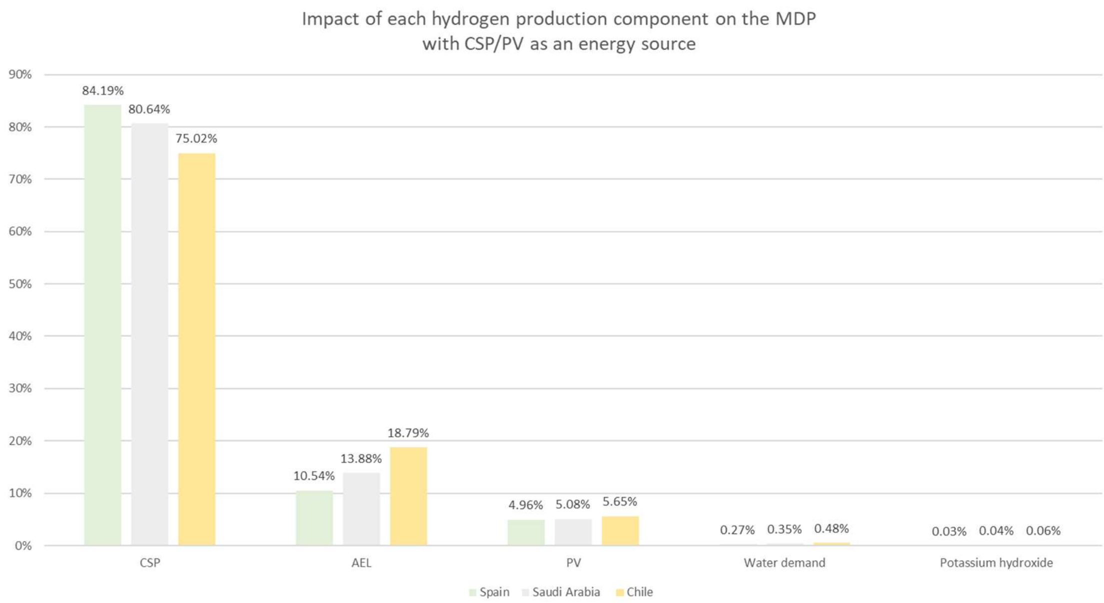


*Figure 15: Impact of each hydrogen production component on the MDP powered by the CSP/PV hybrid system.*

In Figure 15 the impact of each hydrogen production component on the MDP for the different plant locations is presented. The analysis indicates that the predominant technology is CSP, with a range of 82 % to 75 % of the total share. The metal depletion resource consumption is observed to be the highest in Spain, with a value of 0.23 $\frac{kg\ Cu{-}eq}{kg\ H_2}$ and the lowest in Chile, with a value of 0.08 $\frac{kg\ Cu{-}e}{kg\ H_2}$. The alkaline electrolyzer demonstrates notable contributions, ranging from approximately 19 % in Chile to around 15 % in Saudi Arabia. Notably, Spain exhibits the lowest impact, at approximately 11 %, a figure influenced by the substantial levels of solar-generated electricity.

The conducted PV system under consideration has the highest influence in Saudi Arabia, with a proportion of 6.81 %, followed by Spain with 6.67 % and Chile with 5.65 %. The water demand and the potassium hydroxide demand exhibit negligible contributions across all countries, with percentages falling below 0.1 %.

The materials exerting the most substantial influence on the CSP plant and the alkaline electrolyzer are steel (low-alloyed and unalloyed), with an impact of nearly 100 % on metal resource consumption. The pig iron production and its upstream process have the most significant impact on the steel process.

In the production of pig iron, coking coal, which is classified as a critical raw material (CRM) by the European Commission, is employed in the blast furnace process, wherein pig iron is produced. During this process, iron ore is smelted with coke, which is derived from coking coal, and limestone (European Commission, 2023; Feng et al., 2017). According to the European Commission, raw material is designated as critical if it possesses an economic importance and if there is a supply risk related to the limited domestic production. Consequently, the list of critical raw materials predominantly includes rare earth elements, such as coking coal, lithium, and silicon metal. In contrast, a strategic raw material is particularly related to the geopolitical situation of a country where a raw material is mined or produced. It is also related to objectives such as the green deal because of the climate behavior of the raw materials (European Commission, 2023).

In addition to steel, other critical raw materials were utilized. The materials exerting the most significant influence on the PV system are aluminum, silver and copper. Aluminum has been identified as a critical raw material, while copper has been designated as strategic raw material. Silver, however, has not been included in the list of critical or strategic raw materials due to the presence of numerous alternative suppliers (Nassar and Fortier, 2021). The uneven distributing of bauxite ore on a global scale is a primary factor contributing to the categorization of aluminum as a critical raw material. The global supply of this raw material is concentrated in a small number of countries, which makes it fragile for geopolitical risks (European Commission, 2023).

### *3.3.4. Ecotoxicity: terrestrial*

The terrestrial ecotoxicity potential (TAETP) is a metric that quantifies the detrimental impact of toxic substances on terrestrial ecosystems. The primary contributors to this category are the emissions of pesticides into agricultural soil, as well as the use of sulfuric acid and steam during the transformation process. In conjunction with the human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP) and the fresh water ecotoxicity potential (FAETP), the terrestrial ecotoxicity is classified as an environmental toxicity. It is expressed in dichlorobenzene (DCB) equivalents (LC-Impact Consortium, 2019).

The primary contributor to terrestrial ecotoxicity is the requisite electricity for the hydrogen production. Consequently, CSP, in conjunction with heliostats, has the most significant impact on the TAETP within all conducted countries between approximately 75 % to 85 % depending on the DNI. A more detailed examination of the alkaline electrolyzer reveals that the cell stack framework exerts the most significant influence on the TAETP.

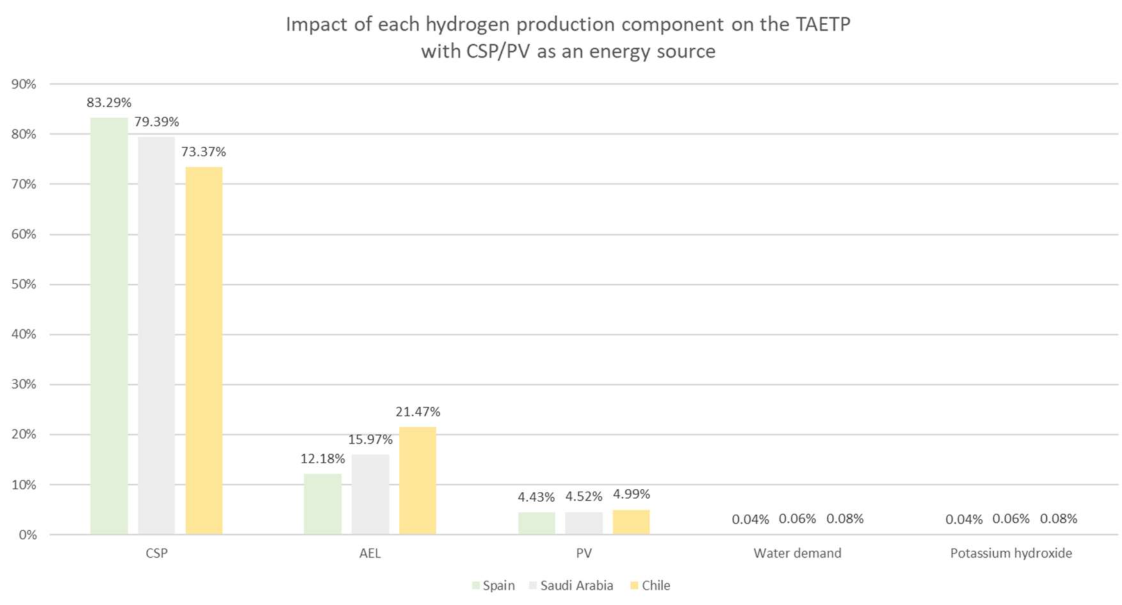


*Figure 16: Impact of each hydrogen production component on the TAETP powered by the CSP/PV hybrid system.*

An examination of the process involved in the production of steel, concrete, and silicon reveals that these materials require a substantial amount of energy. It can be posited that the majority of this energy required is derived from fossil fuels, such as lignite or hard coal. The mining of coal in an open-cast mine results in the production of bauxite. The practice of bauxite mining has been linked to significant environmental consequences. The establishment of opencast bauxite mines often results in the destruction of vast tracts of forest and rainforest, with a significant detrimental impact on the surrounding terrestrial ecosystem (Umweltbundesamt, 2015). In addition to the impact of the production process of steel or silicon, both the PV modules and the heliostats occupy a considerable amount of space. Consequently, these structures exert an unavoidable influence on the landscape, akin to the desertification observed in the respective countries under consideration.

### *3.3.5. Conclusion*

In summary, the findings indicate that solar radiation, and consequently the amount hydrogen produced, exerts a predominant influence on the outcomes. Within each of the four impact categories, Chile consistently exhibited the most negligible impact, as indicated by its highest DNI. Conversely, Spain, with the lowest DNI, consistently exhibited the highest emissions. A notable finding was the detrimental impact of the steel utilization across various impact categories. The analysis indicates that the production of steel, and the codominant energy consumption, exerts the most significant influence on the majority of the categories. The findings also revealed that the alkaline elctrolyzer does not have substantial impact on the emissions. The CSP/PV hybrid system impacts the emissions of the electrochemical hydrogen production, not the electrolyzer itself. The CSP plant had a significantly higher impact on the impact categories compared to the PV plant; however, it should be noted that the CSP plant was also providing a higher share of the electricity. A direct comparison between CSP and PV systems reveals that the latter has a comparatively lower impact on the greenhouse gas emissions. The variation in emissions is influenced by factors such as the location and the production site. On average, the emissions from a PV system are approximately 50 $\frac{g\,CO_2-eq}{kWh}$, while those from a CSP system are around 20 $\frac{g\,CO_2-eq}{kWh}$ (Gasa et al., 2021; IEA PVPS Task 12, 2020; Umweltbundesamt, 2021).

## 3.4. Interpretation, critical review and sensitivity

In the following chapter, the findings from the research and the conducted analysis are outlined and interpreted. The data collected through the life cycle assessment were analyzed using OpenLCA with the Ecoinvent v3.10 database. The results of the LCA are compared with other energy sources and analyzed for their significance.

### *3.4.1. Data quality critical review /uncertainty*

The dataset utilized in this LCA predominantly derives from the Ecoinvent v3.10 database, with no accompanying assessment of the respective processes employed. The origins of the data collected by Ecoinvent for the majority of the raw materials used are identifiable. Consequently, the data quality can be considered as satisfactory, given the predominantly available data sources.

However, for this thesis, every dataset used was analyzed according to the pedigree matrix, which can be found in the appendix under **Error! Reference source not found.**. The pedigree score consists of five levels, with five indicating 'very good'. Table 5 shows the mean pedigree analysis based on Andreas Ciroth's methodology (Ciroth, 2012).

*Table 5: Pedigree matrix - mean of the used Ecoinvent v3.10 datasets.*

| **Pedigree matrix - representive of the used datasets (Ecoinvent v3.10)** | |
|---|---|
| **Category** | **Mean** |
| Data quality rating | 3.6 |
| Geographical correlation | 3.7 |
| Completeness | 4.02 |
| Temporal correlation | 3.88 |
| Data Validation | 4.05 |

As can be seen in Table 5 some of the processes are rated as fair e.g. the three-conductor cables since the litature data is not fully specified, and for the concrete used, they are only partially complete. The description does indicate the year of data collection and the individual responsibility for its entry. The data quality can therefore be assessed as good for most of the processes under consideration.

However, with regard to the independently assessed data, the description of the process used in the Ecoinvent and the sources of the data used sometimes do not provide any information of the data used has been validated by an independent party. Therefore, it can be assumed that the processes used are not independently assessed, which ultimately has a negative impact on the data quality. Additionally, the data quality is adversely affected by the fact that certain processes from the Ecoinvent v3.10 database partially reject their results from over a decade ago. At this point, a discrepancy emerges between the processes and the data utilized by materials in this LCA, as it pertains to the reference year 2020. Furthermore, some of the sources of the materials utilized are not available anymore since for Koj et al. an older Ecoinvent database was being used, this fact influences the data quality also negatively because some used processes were not available anymore.

The data utilized to ascertain the materials of the module in question originates from an article from Koj et al. from 2017. Consequently, the quality of the data can be considered as mostly adequate, as it is derived from Koj et al.`s research and information. However, there are also uncertainties with regard to the processes used, the composition and production phase of which are not clearly delineated from the description in Ecoinvent v3.10. Additionally, there are uncertainties concerning the processes employed, some of which predate the reference year material list by significant margin. The assumption that the CSP storage facility with 14h has an almost equal impact on the emissions mentioned is one of the most uncertain factors, with the greatest impact on the overall CSP system, as the storage facility, in conjunction with the DNI, determines the net electricity generation of the CSP tower plant.

Moreover, meteorological conditions in the utilized countries have been demonstrated to exert an adverse influence on the data quality, as the DNI is found to be contingent upon weather conditions. For the CSP DNI, Fraunhofer data as well as Meteonorm datasets were utilized. For the assessment of the PV system, the solar atlas and the Fraunhofer data were employed for the determination of the utilized DNI. However, there are still uncertainties about the dust on the heliostats as well as on the PV modules.

The utilization of country-specific datasets for the grid mix purposes has been demonstrated to exert a detrimental influence on the quality of data. As previously stated, the grid mix differentiates between northern and southern regions of Chile. However, the Ecoinvent only allows for the utilization of a dataset encompassing a mixture from both northern and southern regions. This limitation has a detrimental effect on the overall impact, as the northern regions exhibit a lower impact on the greenhouse gas emissions, as evidenced by the southern region which does not have as many renewable energy sources.

### *3.4.2. Completeness check*

Regarding the completeness of the LCA, it should be noted that the phases which were under consideration "cradle to gate" are complete, considering the assumptions. However, it is important to acknowledge that the end-of-life phase is as already described in the system boundaries is not part of the process but some of the used Ecoinvent datasets include anyway the end-of-life processes. Since it was also determined that the transportation of the materials utilized will not be a part of this LCA are the processes which were being used complete but some of the used Ecoinvent processes do include already transportation options to various locations which affects the completeness negatively.

Preliminary research suggests that the raw materials used in the mining of copper can be assumed to be complete. This conclusion is based on the documentation viewed and the research and scientific reports read (Ecoinvent v3.10, 2023).

With regard to the adhesive utilized in the assembly of the materials, including for example the glass utilized in the heliostats, as well as the glass employed in the PV modules, and additional materials employed in the alkaline electrolyzer, it can be claimed that its usage was negligible. Consequently, it can be deduced that the adhesive falls under the cut-off criteria. This consideration can also be regarded as complete. The materials used in the alkaline electrolyzer can be regarded as complete, as they were used in the work of Koj et al. and the analysis referenced Ecoinvent datasets. However, it should be noted that certain material datasets utilized in the aforementioned scientific paper were no longer accessible in the updated Ecoinvent database. Nonetheless, the majority of the materials and processes employed can be considered complete. A similar conclusion can be drawn for the material data utilized in the CSP tower system. The materials used in this system were also subjected to analysis and assessment based on the Ecoivent datasets. In the instance, the process can be considered complete.

The solar irradiation utilized was derived from weather data from Meteonorm over a 15-year climate period. Consequently, it can be characterized as complete; however, a certain residual uncertainty persists, as the climate period under consideration extends only until 2015, and the analyzed system pertains to the year 2024.

### *3.4.3. Sensitivity analysis*

For the purposes of this analysis, a CSP/PV hybrid system was selected; however, the majority of LCA studies in this field utilize wind as the primary energy source or they use a gird electricity mix. Since the electricity mix has the highest influence as described in the impact analysis makes a sensitivity analysis in this field significant.

As demonstrated by the analysis and the comparison, the type of electricity utilized for electrochemical hydrogen production with alkaline electrolyzer and exerts a substantial influence on greenhouse gas emissions. The following section examines the impact on the outcomes for different energy supply configurations - such as a grid mix, 100 % CSP, and 100 % PV energy. The analysis aims to elucidate how these energy sources influence the sustainability and feasibility of the electrochemical hydrogen production process.

The various installation locations, namely Spain, Saudi-Arabia and Chile, are subjected for the sensitivity analysis. A closer look is taken at the four impact categories which were analyzed with the CSP/PV hybrid energy source in chapter 3.3 more closely. These four impact categories exhibit disparate hotspots of utilized components and demonstrate the importance of the impact of the energy source of the alkaline electrolyzer during the hydrogen production process. The environmental impact of the installations varies depending on the net electricity yield at each site.

Besides the sensitivity of the chosen energy source, also the chosen impact assessment method has a significant impact on the emissions of the produced electrochemical hydrogen. In following (3.4.4.5.) is also the used ReCiPe method compared with CML method to see the difference impact on the global warming potential.

*3.4.3.1. Global warming potential (comparison grid mixes with CSP/PV)*

As illustrated in Figure 17, a comparison is made between the GWP, measured in kilograms of $CO_2$-equivalent per kilogram of hydrogen ($\frac{kg\ CO_2-eq}{kg\ H_2}$), for two energy scenarios: hydrogen production with the electricity grid mix of the analyzed country is compared to the results of the CSP/PV hybrid system from Chapter 3.3. These scenarios are evaluated across three locations - Chile, Saudi Arabia, and Spain.

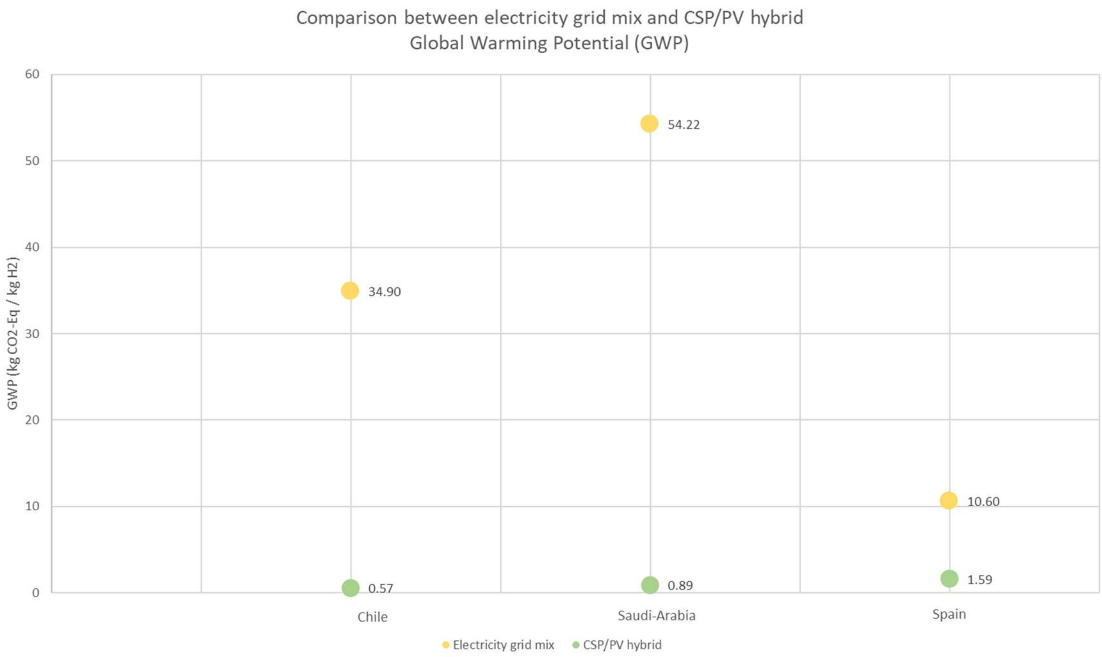


*Figure 17: Comparison between electricity grid mixes and CSP/PV hybrid - GWP.*

The CSP/PV hybrid consistently yields a lower GWP across all locations when compared to the electricity grid mix. The electricity grid mix demonstrates a substantially elevated environmental impact in terms of GWP. The electricity grid mix from Saudi-Arabia exhibits the most substantial environmental impact. A thorough examination of the underlying dataset reveals that the production process utilizes grid mix consisting of natural gas and oil in excess of 99 % (IEA, 2019). This finding is particularly salient in the context of Saudi Arabia’s electricity grid mix, where the utilization of renewables remains minimal. The consequence of this is a staggering increase in emissions, exceeding 6 000 %, when compared to the electrochemical production of hydrogen through a CSP/PV hybrid electrical source.

The GWP of the hydrogen produced with the electricity grid mix of Chile is estimated to be approximately 40 $\frac{kg\ CO_2-eq}{kg\ H_2}$, while the CSP/PV hybrid achieves a substantially lower GWP of close to 0.5 $\frac{kg\ CO_2-eq}{kg\ H_2}$. The emissions resulting from this scenario are lower than those associated with Saudi Arabia but higher than those associated with Spain. The composition of the grid mix primarily consists of oil, accounting for nearly 50 % of the total, with additional contributions from natural gas and coal. In contrast, approximately 20 % of the energy mix consists of biofuels and waste. It is noteworthy that the utilized grid mix is blend of the average Chilean electricity grid mix; however, the mix is expected to improve, as the location of Diego de Almargo, situated in the northern region of Chile, is known for its solar energy resources (IEA, 2019, 2023).

Spain has the lowest emissions, with approximately 10 $\frac{kg\ CO_2-eq}{kg\ H_2}$, the lowest among the three utilized locations. The significant lower emissions for the Spanish electricity grid mix can be attributed to the fact that the electricity grid mix is made about 70 % of electricity sources with around zero $CO_2$-emissions (renewables and nuclear) (IEA, 2019; RED Eléctrica de Espana, 2020).

Overall, the comparison in this chapter shows that electrochemical hydrogen production only makes sense if an electricy mix with a low share of fossil fuels is avaible.

*3.4.3.2. Global warming potential (comparison CSP/PV with CSP and PV)*

Figure 18 compares the GWP, measured in kilograms of $CO_2$-equivalent per kilogram of hydrogen ($\frac{kg\ CO_2-e}{kg\ H_2}$) between the 100 % CSP, 100 % PV and CSP/PV hybrid electricity supplies.

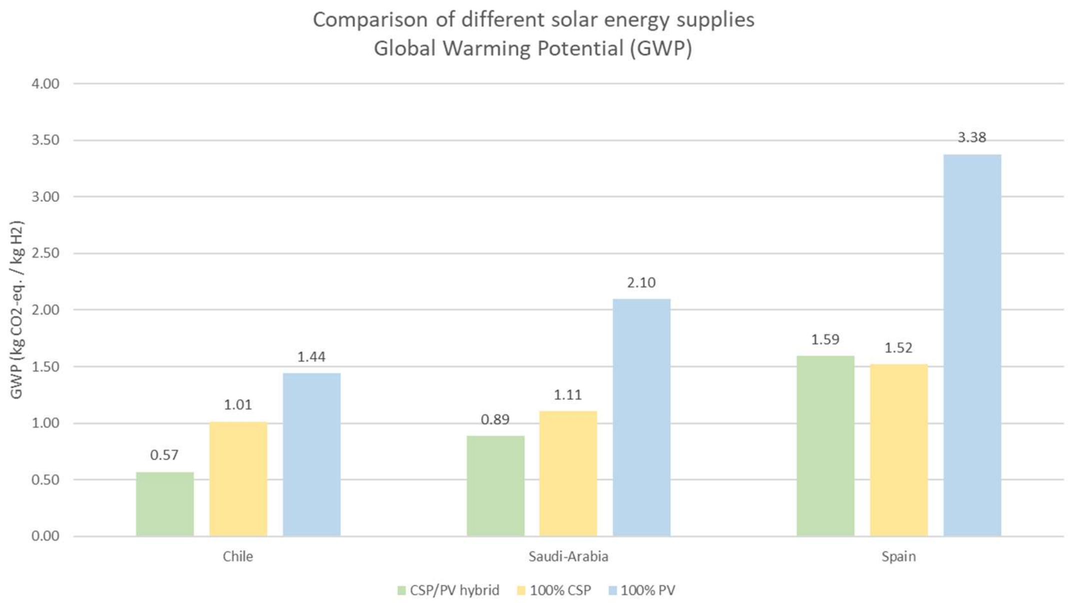


*Figure 18: Sensitivity analysis: comparison of different solar energy supplies (CSP/PV, 100 % CSP and 100 % PV-GWP.*

For the Chile and Saudi Arabia, the hydrogen produced with a CSP/PV hybrid power plant shows a lower GWP than the one produced with other solar power supplies. In Spain the 100 % CSP power supply case has the lowest emissions. For each selected location, 100 % PV has the worst emissions on the GWP. This due to the higher power of the PV system, which had to be higher due to the lack of energy storage to operate the 150 MW alkaline electrolyzer.

In Spain, 100 % PV has the highest emissions compared to the other sites, but this is due to the efficiency of the PV system, which had to have a much higher output of around 268 MW (Appendix D) then the PV systems in the other sites with 170 MW and 210 MW to operate the 150 MW alkaline electrolyzer. The emissions of the 100 % PV system are more than two times higher than the emissions of the other solar energy supplies such as the 100 % CSP plant or the CSP/PV hybrid plant. Chile has the lowest emissions for each solar energy supply, due to the higher solar irradiation.

It is interesting to see, that the emissions for the hybrid system are lower for sites with a DNI around 2000 $\frac{kWh}{m^2a}$ and above 2000 operation hours the PV system and with above 5000 operation hours for the CSP system. Since the hybrid system is also economical, the results show that it is also environmentally better to use the hybrid system for locations with a higher DNI.

Spain has the lowest DNI where the 100 % CSP plant makes more sense from an environmentally point of view, this is due to the fact that the PV plant has here a higher impact because it does not include an energy storage and needs to have a really high power with a lot of PV modules. The production of the PV modules has the biggest impact on the emissions as they are mostly produced in China with an electricity mix that is mostly hard coal.

*3.4.3.3. Marine aquatic ecotoxicity potential (comparison CSP/PV with CSP and PV)*

The results in Figure 19 also show a comparison of the different solar energy supplies but with a focus on the MAETP.

The results show that the impact on the MAETP is the highest for the 100 % CSP plant. This significant impact on the CSP plant is due to the heliostats and carbon steel. Compared to the hydrogen production rate, PV has the lowest hydrogen production rate, but does not contain as much steel, which has a significant impact on the marine aquatic ecotoxicity. The CSP/PV hybrid system has the highest hydrogen production rate and the lowest impact on the water ecotoxicity, except for Spain. With a PV DNI lower than 2000 $\frac{kWh}{m^2\,a}$, the 100 % PV system has a lower impact on water ecotoxicity than the other two technologies.

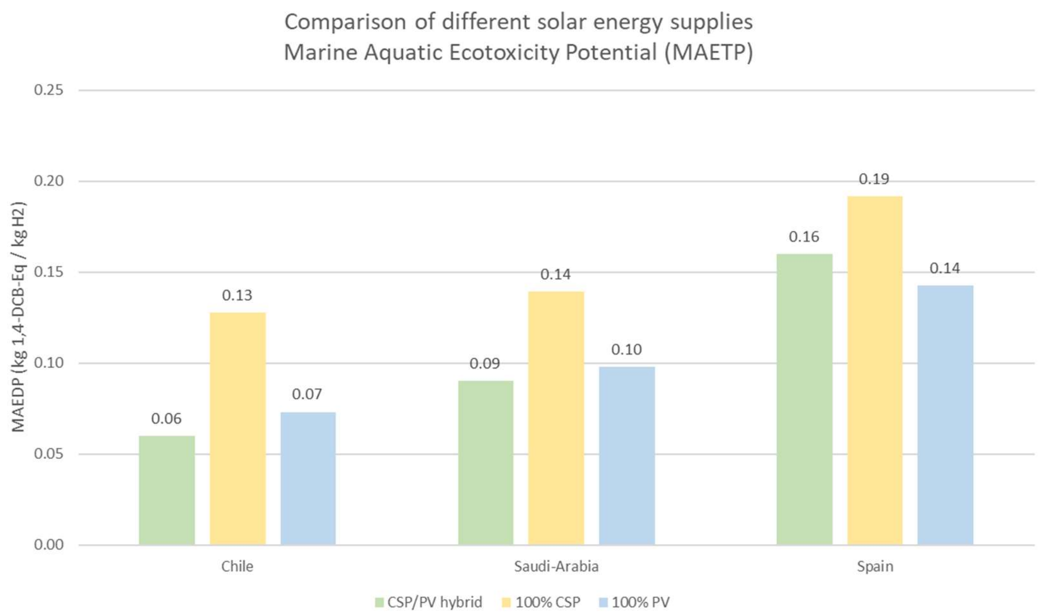


*Figure 19: Sensitivity analysis: comparison of different solar energy supplies (CSP/PV, 100 % CSP and 100 % PV-MAETP.*

Figure 19 also shows that the higher the DNI, the lower the impact of the CSP/PV hybrid system on water ecotoxicity. Chile has the highest DNI and the lowest impact on the water ecotoxicity. The impact is more than 60 % lower than the impact on the water ecotoxicity in Spain.

### *3.4.3.4. Metal depletion potential (comparison CSP/PV with CSP and PV)*

As illustrated in Figure 20, a comparative analysis of various energy sources is presented, with a particular emphasis on the MDP. The CSP/PV hybrid demonstrates a marginal superiority over the other solar energies, albeit exclusively for Chile. In the other two locations, the PV System exhibited a diminished impact on the MDP. A notable finding is that the 100 % CSP system exhibits the greatest impact on the metal depletion potential among the other technologies.

It is noteworthy that the results indicate that a higher DNI results in a less significant impact on the MDP from CSP/PV hybrid option compared to sites with a lower DNI. This effect can be attributed to the fact that a country with a higher solar radiation capacity can produce more hydrogen if solar energy is utilized as the primary energy source.

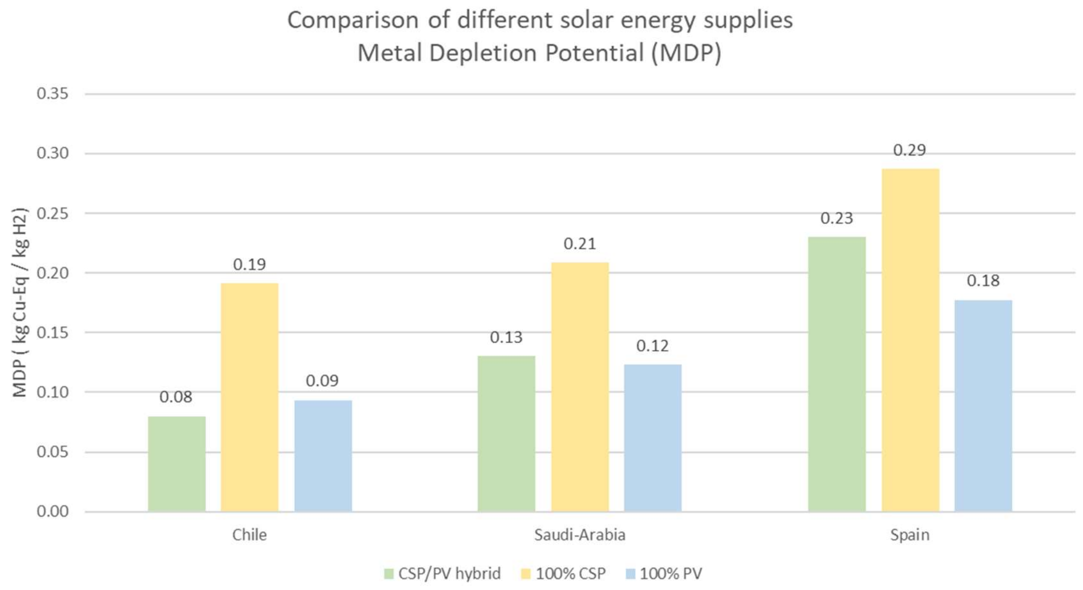


*Figure 20: Sensitivity analysis: comparison of different solar energy supplies (CSP/PV, 100 % CSP and 100 % PV-MDP.*

### *3.4.3.5. Terrestical ecotoxicty potential (comparison CSP/PV with CSP and PV)*

The focus in Figure 21 lies on the terrestical ecotoxicity potential. In comparison, the impact on the TAETP for the CSP/PV hybrid system is significantly lower than for the 100 % CSP plant and 100 % PV systems for Chile.

The high impact for the 100 % CSP system is due to the lower hydrogen production rate. The hydrogen production rate is significantly higher for the hybrid system than for the 100 % CSP and 100 % PV options for the conducted sites. As the production rate is lower, and therefore the efficiency of the whole system, the impact on the 100 % CSP and 100 % PV is higher. However, this result also depends on the location or rather on the DNI. Again, the impact of the CSP/PV hybrid system on the terresticial ecotoxicity is lower in Chile, but in Spain and Saudi Arabia it is slightly worse than the 100 % PV option.

It is interesting to see that the impact is worst for the 100 % CSP plant, but this is also due to the fossil fuel mix used in the production of steel that is required for the CSP plant. This impact of the CSP plant is mainly influenced by the steel production as described in Chapter 3.3.4. Steel production requires a high demand on energy, including fossil fuels such as lignite or hard coal for China, which is the world's largest steel producer. The degradation of lignite and hard coal has a huge impact on the terrestrial ecotoxicity.

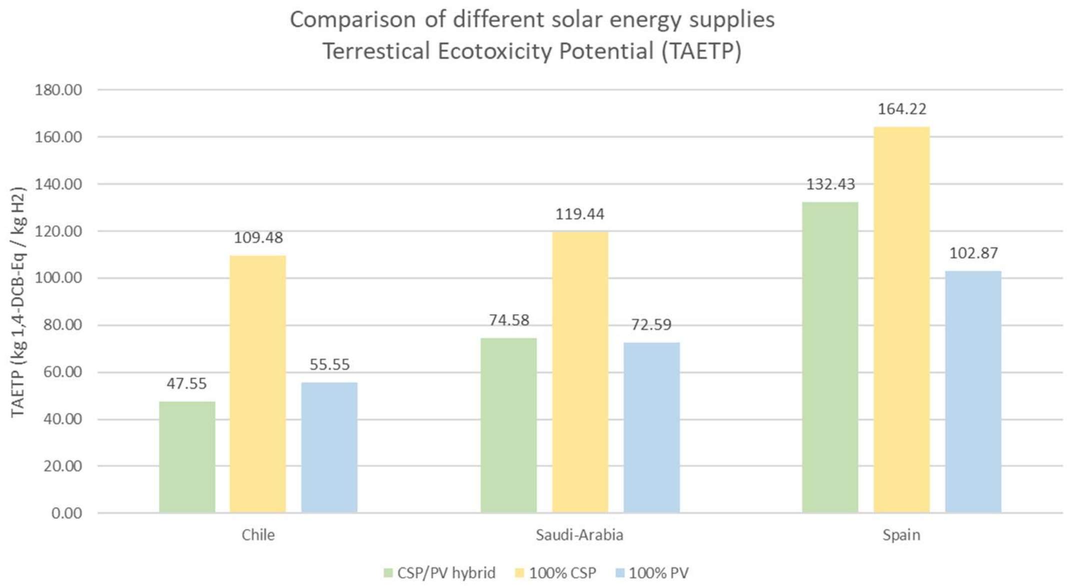


*Figure 21: Sensitivity analysis: comparison of different solar energy supplies (CSP/PV, 100 % CSP and 100 % PV- TAETP.*

Furthermore, the results of Figure 21 illustrate that the impact on the terrestrial ecotoxicity is much worse than that on the aquatic ecotoxicity. The impact on the soil is almost 100 % worse than the impact on the water of the used electrical equipment.

The PV system, or more precisely the PV modules, has the greatest impact on the TAETP. The wafer is the component of the module to which the environmental impact is attributed. More specifically the silicon production has a significant impact on TAETP.

### *3.4.3.6. Global warming potential (comparison ReCiPe and CML)*

Figure 22 compares the GWP of electrochemical hydrogen production with CSP/PV hybrid as energy source at the conducted sites studied using three different impact assessment methods to see the influence of the chosen assessment method on the results.

As shown in Figure 22, the three selected assessment methods are ReCiPe (midpoint) no LT, ReCiPe (midpoint) LT and CML 2016. The ReCiPe (midpoint) no LT method calculated the GWP without considering long-term effects. In contrast, the ReCiPe (midpoint) LT method incorporates long-term impacts into the GWP calculation. The CML 2016 method is another method that considers long-term impacts, starting from the year 2016.

Spain shows the highest GWP across all considered sites, but it is interesting to note that the values for ReCiPe (midpoint) LT and CML 2016 are almost similar because they have a percentage deviation of around 3 %. The effect that the results of CML 2016 and of ReCiPe (midpoint) LT are similar is also the same for Saudi Arabia and Chile, here they differ also approximately 3 %. But for each country has the ReCiPe no LT has the lowest emissions, which is due to the fact that the GWP calculation does not include long-term effects. It is noteworthy that the results are significantly better with an impact assessment method that does not include long-term effects increases with the increase in solar irradiation. Moreover, should be noted that the percentage deviation between ReCiPe (midpoint) LT and ReCiPe (midpoint) no LT differ between the sites. In Spain the percentage deviation amounts approximately 12 % while in Saudia Arabia and Chile 33 % and 50 %.

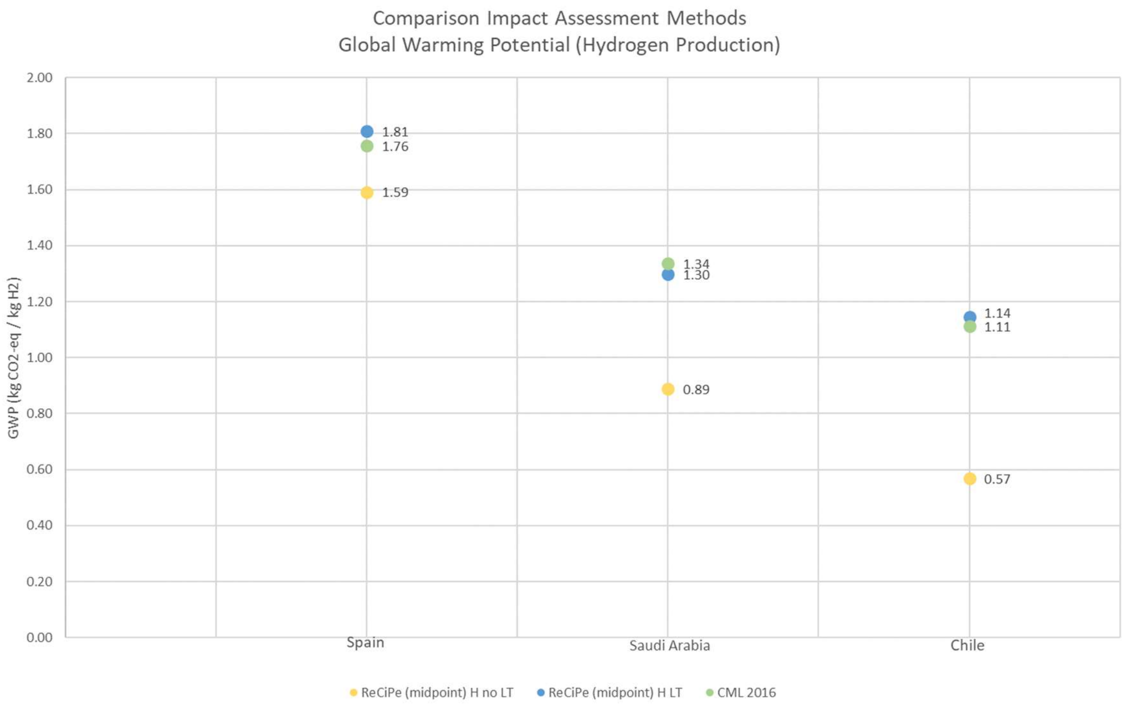


*Figure 22: Sensitivity analysis: comparison of different impact assessment methods (ReCiPe and CML) - GWP.*

### *3.4.4. Consistency test*

The assumptions, allocations, and cut-off criteria are consistent across all processes. The impact assessment is also based entirely on the ReCiPe method and can therefore be regarded as consistent. The data utilized in these processes has been implemented in a consistent manner. However, the scope of the study is not without limitations. For instance, the three-line cable, which relates to the year 2017 in both production countries under consideration, is less consistent due to the information on the material composition of the CSP tower plant relating to the year 2020. In certain instances, other processes employed, such as those involving electrical cables, also refer to earlier years, thereby contributing to the observed inconsistencies. In addition to the temporal inconsistencies, the processes also demonstrate deficiencies in terms of location. For numerous processes, the specific locations could not be entered, necessitating the selection of “General” as the location, with “Rest of the World” (RoW) frequently being used as the unspecified location. The data used in this study is less consistent due to the use of weather data, which calculates the DNI of the locations used in each case, referring to a period well before 2024.

However, it is noteworthy that the data exhibits a greater degree and consistency when compared to other data sets, as it encompasses a broader time period, including significant weather phenomena such as El Niño in the balance. This comprehensive scope contributes to the enhanced consistency of the data.

# 4. Discussion

The central objective of this thesis was to comparatively analyze various solar energy sources as potential candidates to produce hydrogen through electrochemical means. In addition, it sought to elucidate the respective merits and drawbacks of these energy sources with respect to their impact in the overall process of electrochemical hydrogen production. The objective of this bachelor’s thesis was to examine the influence of the CSP/hybrid system, which has economic advantages over CSP and PV systems alone, as well as environmental benefits.

## 4.1. Summary

All in all, it can be said that the environmental impacts differ between the analyzed impact categories. The main focus of this thesis was the impact on the greenhouse gas emissions. With the focus on this criterion, it can be said that the CSP/PV hybrid system has lower emissions than the two other scenarios with 100 % CSP or 100 % PV. It is interesting to note that from an economical point of view the CSP/PV hybrid system also has advantages compared to systems which rely only on one solar technology. The results show that environmentally the CSP/PV hybrid technology is also a better option on the greenhouse gas emissions.

Furthermore, it should be noted that the CSP/PV hybrid system has also mostly a lower impact on the other impact categories compared to the 100 % CSP and the 100 % PV option. This is mainly due to the mining of raw materials and the electricity mix which was being used during the production process of the used materials such as steel or silicon. In addition, the hydrogen production rate is definitely higher with the hybrid system. In conclusion the electricity mix which was used during the production process has a significant impact on the emissions. Since China is the country where most of the materials are produced and it has an enormous growth in renewable energies, it can be said that this negative impact will be reduced in the next years. But nevertheless, a production in a country with less fossil fuels and more renewable energies could have an enormous impact on the emissions. The impact of the grid mixes of countries with less renewable energies also showed how important it is for a climate neutral future that renewable energies are used for the electrochemical hydrogen production.

## 4.2. Validation / Classification of the results

As shown in the analysis, the type of electricity used for the alkaline electrolyzer and the hydrogen production has a significant impact on greenhouse gas emissions. A comparison of the analyzed results with other technologies used to produce hydrogen shows how to classify the conducted results. The study results are validated by comparing them with other studies investigating electrochemical hydrogen production usinf renewable energy sources. This is discussed in detail below.

The technologies analyzed include steam methane reforming (SMR), also known as grey hydrogen, SMR with carbon capture and storage (CCS) (blue hydrogen), pyrolysis process (turquoise hydrogen), and various solar-based production technologies (CSP/PV hybrid).

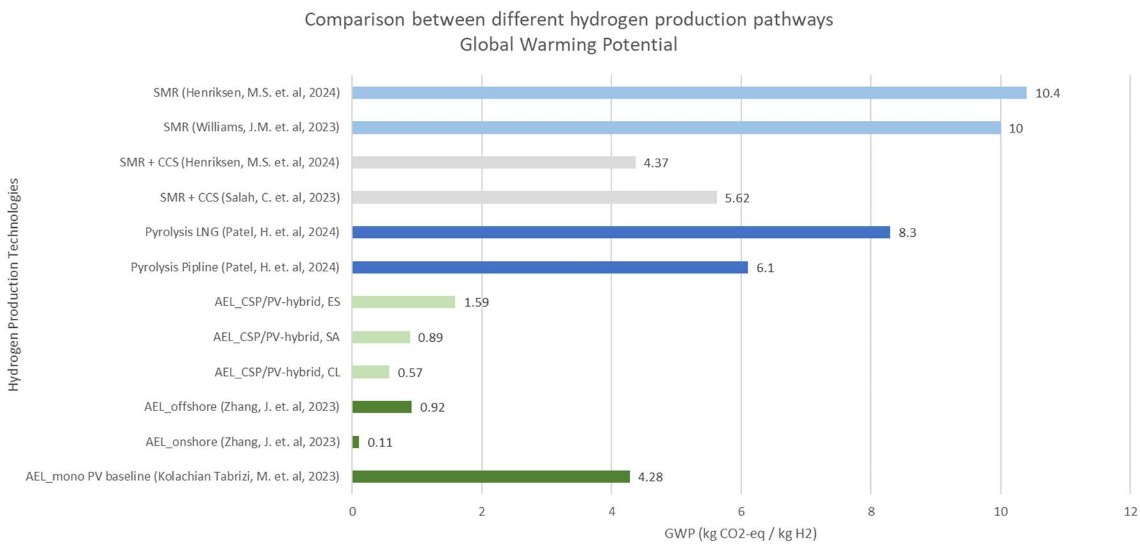


*Figure 23: Comparison between different H2-Production pathways (GWP) (Maniscalco et al., 2024).*

As illustrated in Figure 23 different hydrogen pathways, measured in kg $CO_2$-eq per kg of $H_2$ show different results on the greenhouse gas emissions. Hydrogen produced through the SMR process has the highest impact with 10.40 $\frac{kg\ CO_2-eq}{kg\ H_2}$ compared to the other hydrogen production pathways (Henriksen et al., 2024). The CSP/PV hybrid technology in Chile ($0.57\ \frac{kg\ CO_2{-}e}{kg\ H_2}$) reduces the emissions of hydrogen by approximately 94.5 % compared to convential SMR ($10.40\ \frac{kg\ CO_2{-}e}{kg\ H_2}$).

As illustrated in Figure 23, the impact of the hybrid system is contingent on its geographical location and the renewable technology employed as an electrolyzer energy source. The alkaline electrolyzer, powered by onshore wind, exhibits the lowest emissions; however, this is contingent on the geographical location. In LCA results are further influenced by the location of the wind turbine, which is identified as a key factor (Patel et al., 2024). Additionally, it is noteworthy that onshore wind energy has lower GWP compared to solar enery sources as reported (Torres and Petrakopoulou, 2022).

Additionally, the pyrolysis and the SMR with CCS pathways exhibit significantly reduced emissions compared to the most prevalent hydrogen production technology, the SMR pathway. However, these pathways still exceed the emissions of the electrochemical hydrogen production pathways. It is noteworthy that the majority of the results indicate a lifetime of 20 to 25 years; but, a higher lifetime will eventually lead to reduced emissions. Furthermore, it is also noteworthy that the results are not exclusively based on the selected locations but reflect a broader tendency.

The classification of the results further elucidates that hydrogen is not a homogeneous entity; it is imperative to differentiate between hydrogen production pathways due to their substantial impact on greenhouse gas emissions.

## 4.3. Outlook

Since the CSP/PV hybrid system also shows environmental benefits especially on the global warming potential, the hybrid system would be an economically and ecologically promising option for electrochemical hydrogen production in locations with a high solar irradiation.

The fact that the environmental impact of the hybrid system depends on the solar irradiation will help future studies to find the perfect renewable energy source for each considered location. The realization that the hydrogen production rate could be much higher with the hybrid system compared to CSP or PV as energy sources will help to better understand how important the energy source for the alkaline electrolyzer is.

In subsequent LCAs, it would be worthwhile to examine the impact of incorporating a battery storage system within the PV system, and to contrast these results with those of the hybrid system. From an economic perspective, it is advantageous to investigate this option, as it is a crucial factor in the advancement of technology when it is economically viable. Additionally, it would be worthwhile to examine the results of the hybrid system in the context of the social life cycle assessment (SLCA). If the hybrid system proves to be environmentally and economically viable, as previously indicated, the social LCA may also support its sustainability. If the results of this analysis align with the findings of this thesis, the hybrid technology could be designated as sustainable across all significant sustainability domains.

Another important parameter that should be analyzed in future LCA studies is the impact of the steel production process. Given the fact that steel has been demonstrated to have the greatest impact on the greenhouse gases emissions and on the majority of the other impact categories it will be of interest to observe how the impact of electrochemical hydrogen production will altered by material substitution or by steel that is produced with a renewable electricity mix.

It is imperative that future studies explore how the results are affected if the LCA is conducted as a prospective LCA. Conducting a prospective LCA, encompassing diverse future scenarios (optimistic, realistic or pessimistic), is imperative to effectively plan for a better future. Demonstrating how the environmental impact and other impact categories might alter their results with a future design is crucial. It is crucial to acknowledge that prospective LCA studies are contingent on the designated location, particularly in the context of climate change. Projections indicate an increase in extreme weather events, which may result in an escalated utilization of heliostats and PV modules, consequently leading to a diminished hydrogen field.

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# Appendix

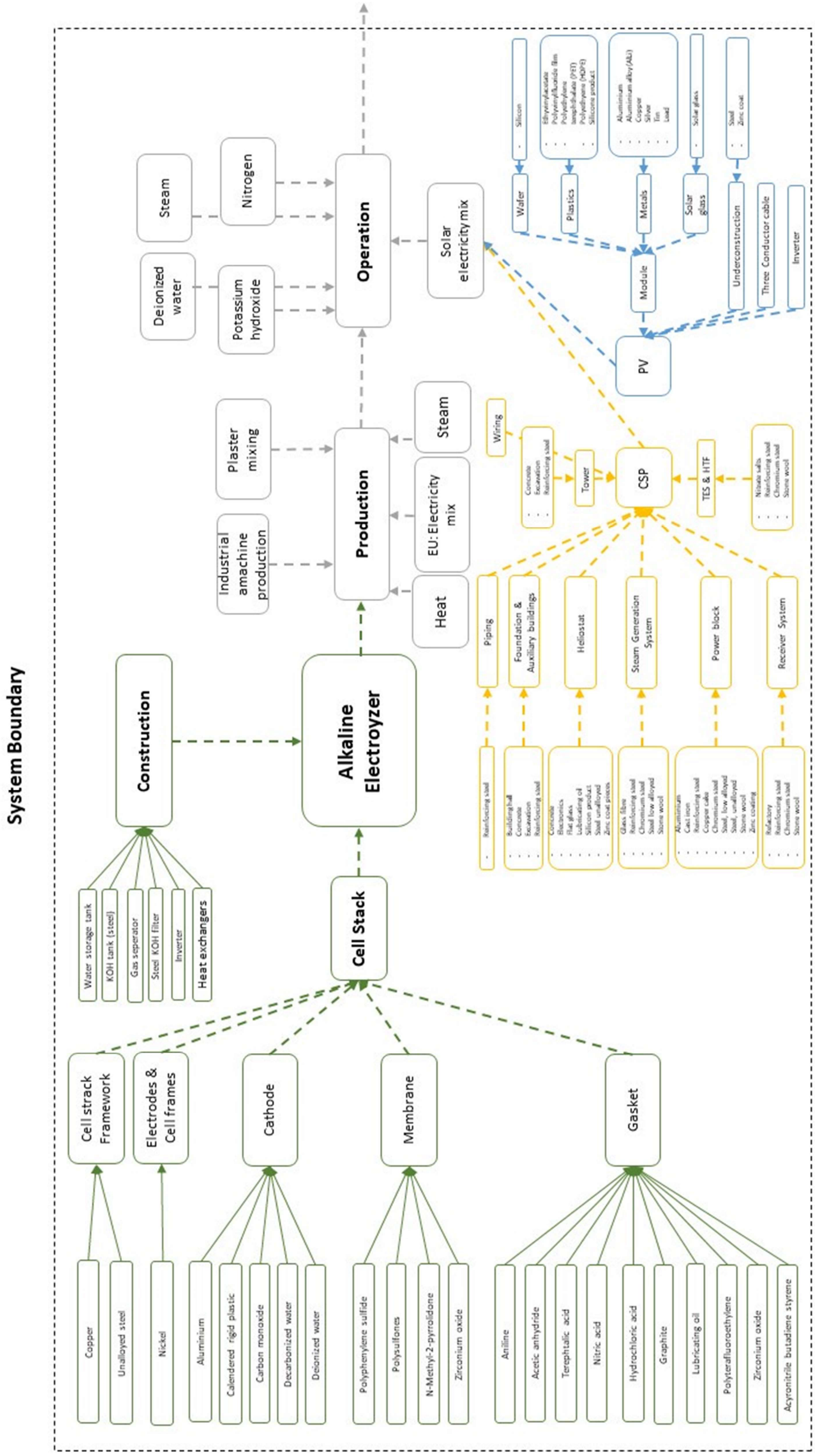


*Figure 24: System flow diagram - AEL/CSP and PV.*

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