Multisector collaboration: The case of desalination and green hydrogen production in Chile

Master's Thesis - MSc Sustainable Business and Innovation

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Abstract

Water scarcity and energy transition are two critical challenges today. To address them, this research seeks to explore potential synergies of collaboration between the desalination and green hydrogen production sectors, using northern Chile's Coquimbo Region as a case study, where both challenges coexist. The objective of the study is to identify whether interactions exist and what the drivers and barriers to interaction are in order to achieve mutually beneficial collaboration. Given the focus on the importance of interactions between sectors, this research is based on the Multi-sector Dynamics (MSD) framework using a qualitative methodology consisting of semi-structured interviews with stakeholders from both sectors, local residents and regulatory experts. The findings show that there are interactions between the two sectors, mainly in the form of resource flows; however, this collaboration is still in its early stages. In addition, the results show a series of technical, economic, regulatory and social drivers and barriers that promote and hinder collaboration between sectors, as well as a series of conditions that could further benefit collaboration. This research contributes to the development of MSD by studying sectors with little interaction and in the early stages of collaboration, highlighting mainly the need to incorporate levels of collaboration maturity into the framework. At a practical level, the study reveals specific recommendations focused on industry actors and policymakers. Finally, the study concludes that while there is some collaboration between sectors, there is still work to be done to make this collaboration a real opportunity for both sectors to address the challenges of water scarcity and energy transition together.

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1. Introduction

The global population has been growing at a rapid pace over the last few decades, surpassing 8 billion people in 2022 (UN., 2022). This growth has intensified the demand for resources, particularly water, leading to three main challenges: accessibility, water quality and geographical distribution (Agnew, 2011). Seawater accounts for 97% of the Earth's water, yet it cannot be directly used as potable water (Issac et. al., 2021). Moreover, it is not feasible to access all the remaining 3% of freshwater, especially groundwater and frozen water (Gleick et. al., 2021). Furthermore, the location of freshwater resources is not always aligned with the areas where they are needed, for example coastal arid regions such as in the Middle East or coastal Latin America (Kuzma et. al., 2023).

For water to be classified as potable, it must meet certain quality requirements. Therefore, one of the main water issues is related to quality rather than quantity (Morin-Crini et. al., 2022). These limitations contribute to water scarcity, which Gleick et. al. (2021, p. 321) define as “(water) scarcity in the context of human social, economic, and health needs arises in particular places or at particular times when human demand for water may exceed the stocks or flows of water on which those demands depend.” According to the United Nations, in 2022 approximately half of the world's population experienced water scarcity and this portion is likely to increase by 2030 (United Nations, 2024).

Given the challenges of water scarcity, technological developments such as desalination have made it possible to produce freshwater that was previously unavailable. Desalination is a process that produces freshwater from seawater or brackish water (Curto et. al., 2021). The global capacity of desalination plants has expanded exponentially over the past 30 years, with over 15,000 operational plants producing 100 million m^3/day by 2020 (Angelakis et. al., 2021). The most widely used desalination process is reverse osmosis, which presents two significant challenges.

Reverse osmosis is an energy intensive process that requires an average of 4.5 kilowatt-hour (kWh) to produce 1 m^3 of freshwater, mainly due to the use of high-pressure pumps (Elsaid et. al., 2020). In order to provide context, the average energy requirement from extraction to drinking water supply for surface water (rivers or lake water) and groundwater is 0.37 kWh/m^3 and 0.48

kWh/m^3, respectively (Kariman et. al., 2023), which is roughly 10 times lower than reverse osmosis.

In addition to its energy demands, desalination faces a waste management challenge. The process yields two outputs: freshwater and highly concentrated salt water, termed brine. In most cases brine is discharged back into the ocean, which has a negative impact on the marine ecosystem such as alterations in sea salinity, temperature and water circulation patterns (Elsaid et. al., 2020).

The majority of research to date has focused on potential solutions to the challenges of energy intensity and brine management (Darre & Toor, 2018). New advances in technology aim to make the reverse osmosis process more efficient to reduce the energy required per cubic metre, but the research focus has been on implementing the use of renewable energies (Saadat et. al., 2018), because most desalination plants worldwide currently use fossil fuels to produce the electricity needed in the process (Qadir et. al., 2022).

From all the renewable energy sources, mainly solar energy had been studied in a direct and indirect way (Saadat et. al., 2018). The direct use of solar energy simulates the water cycle, in which water is heated, evaporated and then condensed to obtain water free of salt and other sediments (Saadat et. al., 2018). This application is in a development stage and has been used in small scale plants, which have low efficiency and require large areas to stimulate water evaporation (Tiwari et. al., 2023). The indirect pathway is the use of solar panels to produce electricity from radiation (Saadat et. al., 2018), which is considered as suitable for medium- to large-scale applications (Tiwari et. al., 2023) as evidenced by the Adelaide Desalination Plant in Australia, which is entirely powered by renewable energy (Darre & Toor, 2018).

To address the second challenge of desalination plants, researchers have focused on the development of innovative solutions to reduce the impact of brine discharge, for example the use of diffusers to disperse the highly concentrated brine over a broader area (Panagopoulos et. al., 2020). However, research into the utilisation of brine as a valuable resource remains limited. Mavukkandy et. al. (2019) explores the opportunities of brine mining, whereby valuable minerals are recovered from brine, such as uranium, lithium, and rubidium. The author states that given the lack of extensive research on this domain and limited number of pilots, brine mining is technically feasible but remains economically unviable.

One particular application that could overcome both challenges, is the use of brine for hydrogen production. Hydrogen is considered an energy carrier that can be produced, stored, transported and finally used as a fuel or converted into electricity (Rosen et. al., 2016). Renewable energies, such as solar and wind, are intermittent, so it is challenging to rely on them for a constant supply of energy. Nonetheless, hydrogen can be produced from the above-mentioned sources and then stored for use when there is not enough radiation or wind to supply the energy demand (Ma et. al., 2024). In addition, using hydrogen to produce electricity does not generate CO_2 emissions or other pollutants (Incer-Valverde et. al., 2023). Therefore, hydrogen could be used to power a desalination plant and partially overcome the energy challenge.

Most hydrogen is produced from fossil fuels and is known as “grey hydrogen”, while “green hydrogen” is produced by a process named electrolysis using renewable energy sources. (Incer-Valverde et. al., 2023). Nevertheless, one of the main challenges for green hydrogen is economic feasibility (Bade et al., 2024), mainly due to the technology used and the energy source. For example, green hydrogen has a production cost of between €2.2 and €8.2 per kg of hydrogen, while grey hydrogen costs between €0.8 and €2.1 per kg (Ajanovic et. al., 2022).

Water electrolysis is a process used to produce hydrogen by exposing a solution of water into electricity to isolate the molecules of hydrogen and oxygen (Chatenet et. al., 2022). Pure water does not conduct electricity, so minerals must be present in the solution in order to enable the electrolysis process (Shih et. al., 2022). Brine contains a high concentration of minerals that can take on the role of electrical conduction. Therefore, this potential resource overlap could overcome the waste management challenge.

The electrolysis process does not eliminate the fact that there is a liquid residue. However, during the salty water electrolysis process, the liquid solution transforms into hypochlorous acid, which is used in the chemical industry to produce cosmetics, disinfectants and other cleaning products (Kieu, 2023). Therefore, at the end of the process, there will no longer be waste, but rather a valuable raw material for other industries. Figure 1 shows a diagram of the aforementioned application.

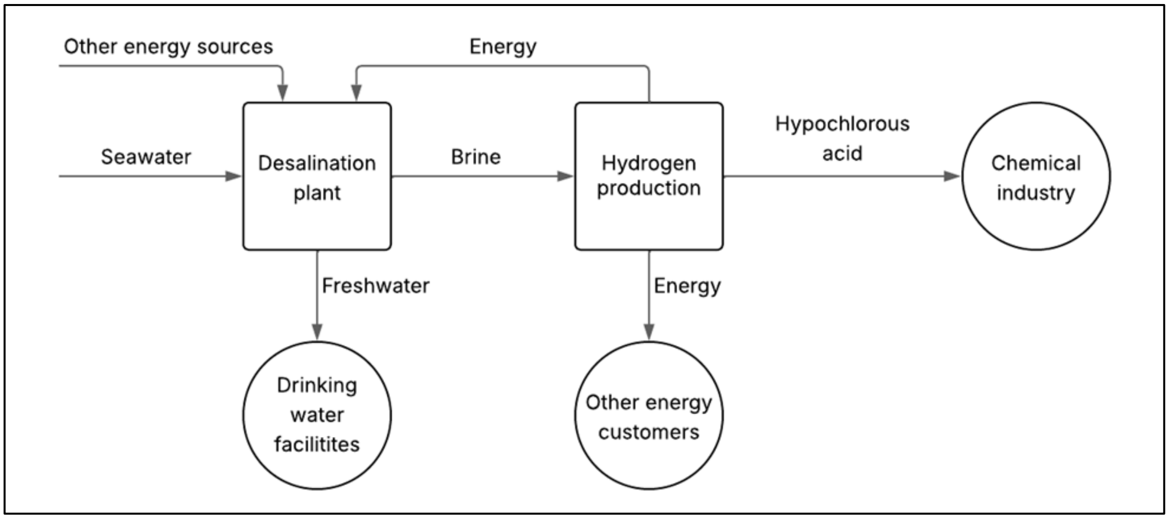

Figure 1: Brine electrolysis diagram.

To achieve such synergies, the desalination and hydrogen industries need to become more integrated. However, interactions between sectors can often be challenging, including managing stakeholder interests, resource conflicts, and data sharing and protection (Brandt & Siebert, 2022). The Multi-sector Dynamics (MSD) framework can help to identify technical, economic, regulatory and social opportunities and challenges of a potential collaboration between sectors and provide insights on how to address them. Srikrishnan et. al. (2022, p. 2) defines a multi-sector system as “set of interacting sectors that yield emergent dynamics beyond that which could be predicted from each sector alone”. MSD was used to detect if there were interactions between sectors, and how to build and enhance them in order to create a new system that benefits both parties and the society involved (Andersen et. al., 2023).

Desalination and green hydrogen are key technologies that are aligned with the global challenges of water scarcity and sustainable energy transition. However, academic literature had focused on analysing these sectors in isolation. For this reason, knowledge is limited about the potential economic, social, and environmental benefits that could be generated by a multi-sector collaboration. Therefore, this research focuses on applying the MSD framework to assess the research gap by identifying opportunities and challenges in a multi-sector system using a single case study.

The Coquimbo Region, northern Chile, is facing a severe water shortage due to a prolonged drought and intensive use of water resources by industries such as mining and agriculture (Salinas et. al., 2016). Therefore, more than 30,000 people receive potable water from trucks, and local authorities expect this number to increase in the future due to the drought (Varela, 2024).

By March 2023, Chile had 22 desalination plants providing a total of 268 million m^3 per year of desalinated water, of which only three were intended to produce drinking water, but none were in the Coquimbo Region (Fuentealba Pizarro, 2024). To address the water scarcity in the region, the national government announced a tender for the construction of a desalination plant in Coquimbo, which will benefit 540,000 people in 2029 (Cabrera Cortés, 2024).

In parallel, the Ministry of Energy has considered the Coquimbo Region to be one of the most sustainable areas in the country in terms of electricity generation, given that in 2022, the region's electricity generation was 2,454.8 GWh, of which 64% was wind energy, 29% solar, 1% hydroelectric, and the remaining 6% from backup power plants (Ministry of Energy, 2023). Additionally, Chile's decarbonisation plans include a Green Hydrogen Action Plan, in which green hydrogen is projected to account for 16–18% of national energy consumption (Gobierno de Chile, 2024). Given the urgency of developing solutions to water scarcity and the pursuit of achieving the energy transition goals, the following research questions were proposed:

How do the desalination and hydrogen production sectors interact in Chile?

What are the drivers and barriers for a successful multi-sector system between desalination and hydrogen production to achieve a mutually beneficial collaboration in Chile?

This study contributed scientifically to expanding the MSD framework by studying a relatively unexplored interaction between the desalination and hydrogen production sectors. The case study bases the interaction on the valorisation of brine as a waste product between sectors that do not commonly interact in this way.

Although the study was based in northern Chile, it focused on two challenges that are important for society in other arid areas such as the Middle East. In addition, the study analysed the possibility of collaboration in a comprehensive manner, identifying potential barriers and drivers of interaction in technical, economic, regulatory and social areas. In this way, this study provides relevant insights for decision-makers seeking sustainable solutions.

2. Theory

2.1. Multi-sector Dynamics background

The Multi-sector Dynamics (MSD) framework is an emerging approach used to understand complex synergies between multiple sectors or systems, such as energy, water, food and transportation (Andersen & Geels, 2023). In contrast to single-system frameworks, MSD put emphasis on the dynamics that occur when multiple systems interact between each other generating outcomes that cannot be achieved in isolation (Reed et. al., 2022). For example, the transportation sector must work together with the energy sector to achieve a successful electrification, which is unlikely to happen if there is no synergy between sectors. This perspective is important when it comes to dealing with the global challenges of sustainable transition (Rosenbloom, 2020). To illustrate the potential outcome of system interactions, Grüning et. al. (2021) studied MSD in circular economy, and they demonstrated that interaction between systems (such as agriculture and water) can design a new system in which waste is reduced and thus optimise the use of resources.

The MSD framework builds on the theoretical foundations of the Multilevel Perspective (MLP), which has been widely used in sustainability transition studies (Andersen & Geels, 2023). MLP focuses on the interaction between niche innovations, regime structures and socio-technical landscapes, providing a framework for analysing transitions within individual systems (Geels, 2002). However, as the study of sustainability transitions has grown, limitations of the MLP have become evident (Geels, 2011). For example, while the MLP explores how emerging innovations disrupt established regimes within a domain, it is limited in addressing interactions and resource flows between multiple systems, such as the overlap between energy and transport systems during electrification efforts (Andersen & Geels, 2023). The MSD framework was developed to address these deficiencies as no system functions in isolation. To address these interdependencies, an analytical approach is needed that not only identifies the complexity of multi-systems but also helps to build and develop the necessary connections (Andersen et. al., 2023). Given that the purpose of this study was based on the interaction between sectors, it was appropriate to use MSD.

In the MSD context, **sectors** are defined as distinct areas of economic activity that relate to specific industries, services and stakeholders (Reed et. al., 2022). Each sector operates within its regulatory, technical and economic boundaries; however, they might interact and depend on each other, especially in complex systems (Löhr et. al., 2024). For example, food, water and energy sectors are interconnected in a way that water fulfil the service of irrigation, drinking water and hydropower. The two main sectors within this study are water and energy sector. The former is responsible of collection, supply, distribution and management of water resources (Zarghami et. al., 2018), while the latter is involved in the production, distribution and utilization of energy (Kahsar, 2023). Some of the actors involved in these two sectors are industry actors, environmental organizations, government agencies and society.

Moreover, **interactions** refer to the ways in which different sectors, systems or actors influence each other through resource flows, operational dependencies and feedback mechanisms (Reed et. al., 2022). Resource flow refers to the exchange of physical, financial and/or knowledge resources between two or more institutions. Operational dependencies occur when sectors share processes or infrastructure, creating dependencies between them. Feedback mechanisms occur when a change in one sector creates a benefit or challenge in the other.

For example, the construction of a dam may have a multi-purpose, because it can be used to generate electricity and to store water. Firstly, the two sectors interact because they use water as a common resource. Additionally, the sectors share the same structure in part of their processes, creating interdependence between them. Finally, if it is decided to increase hydropower production, it may create a challenge to control water levels for the future. In this example the sectors interact due to the three mechanisms described above, but this is not always the case. Sectors may interact by one of the above mechanisms, a combination of two of them or all three simultaneously. For MSD it is crucial to understand how changes or innovations in one sector can affect others, leading to synergies or conflicts. For that reason, Wise et. al. (2019) highlights the importance of MSD for business and regulatory decision-making processes, ensuring that interventions in one sector do not undermine another.

This framework has also been developed to address resource competition and identify trade-offs between sectors (Moallemi et. al., 2024). A potential benefit in one sector could generate a negative externality in other sector, thus MSD provides an approach to understand these complexities and provide insights to design mechanisms that leverage synergies and mitigate conflicts (Löhr et. al., 2024). For example, the electrification of transport system depends not only in the development of electric vehicles, but also in how prepared the energy system is to supply a higher demand. The Netherlands is a good example for the previous, because the grid is already facing challenges due to its congestion and electrification is worsening the problem (Damianakis et. al., 2023).

Drivers are forces that promote or enable collaborations across sectors, while **barriers** are any type of obstacle or challenge that hinders effective interaction or collaboration between sectors (Srikrishnan et. al., 2022).

Drivers and barriers can be classified into technical, economic, regulatory and social dimensions (Tura et. al., 2019). The technical dimension includes factors such as technologies, knowledge and infrastructure that enable or hinder innovation. The economic dimension relates to the financial opportunities and challenges of multisectoral integration. The regulatory dimension includes policies and laws that can be supportive or restrictive to sector interaction. The social dimension concerns society and how it is affected by potential collaboration.

The framework allowed an understanding of how these systems can be strengthened by working together. A **mutually beneficial collaboration**, also known as win-win, refers to a partnership in which multiple sectors achieve mutual benefits that cannot be achieved by each sector working in isolation (Reed et. al., 2022). For this type of relationship to be successful, it is crucial to establish good long-term interaction between stakeholders within each sector (Parida et. al., 2013). An example that illustrates the above are the collaborations between the agricultural and energy sectors. The use of “agrivoltaics” is the combination of agricultural soil with solar production on it (Sirnik et. al., 2024). The solar panels protect the plants from excess sun and a moist soil helps to regulate the temperature of the panels to prevent them from overheating increasing their efficiency (Sirnik et. al., 2024). In this way, this collaboration delivers benefits to both sectors and helps to overcome conflicts of extensive land use in each sector.

For the development of this study, MSD provides a framework for investigating the synergies and challenges between desalination and green hydrogen production. MSD provided the tools to explore the interdependencies between the two sectors and the drivers and barriers for effective collaboration in the Coquimbo Region in Chile.

2.2. Conceptual model

The conceptual model in Figure 2 shows the MSD framework, in which the interaction between the energy and water sectors can be seen. These interactions can be created through resource flows, operational dependencies and feedback mechanisms as shown with the coloured arrows. Although all arrows are shown as bidirectional and of the same size, it may be that the interaction is unidirectional, and that one mechanism predominates over the others.

Sectors need to benefit from drivers and overcome barriers in their four dimensions to achieve successful collaboration. However, the way in which the sectors interact is part of the study's objective and was a key element to be researched. Therefore, the visual model summarizes the MSD framework and served as a guide to develop the methodology needed to answer the research questions.

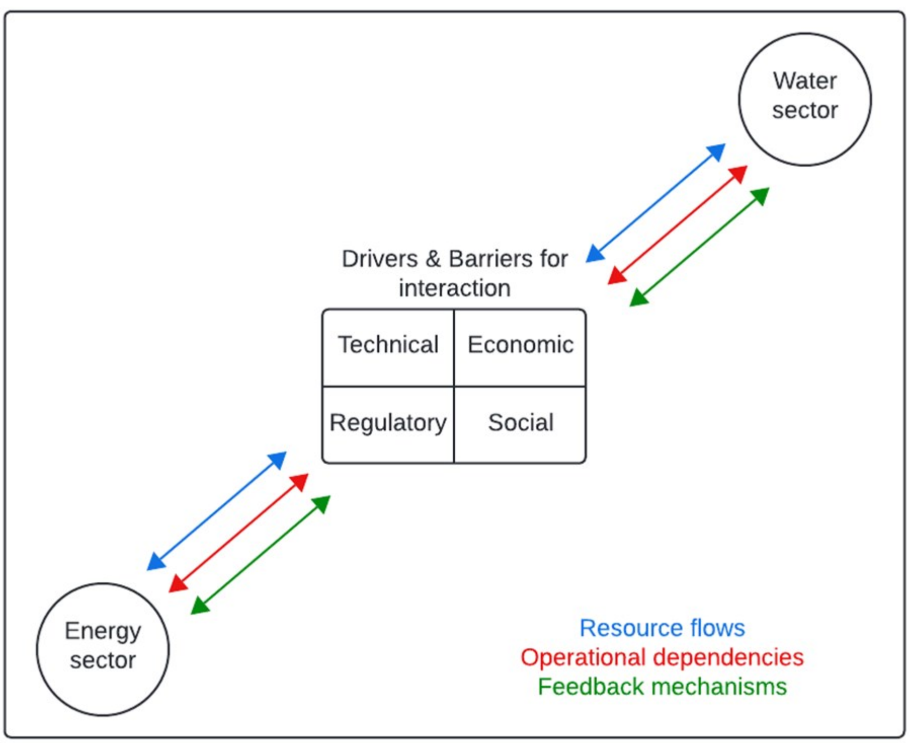

Figure 2: Conceptual model of MSD.

3. Methodology

3.1. Research design

The objective of this study was to identify the challenges and opportunities for collaboration between the desalination and green hydrogen production using MSD framework. Therefore, the research was designed to collect data from both sectors and other stakeholders related to these sectors.

A qualitative study was performed by using a single case study located in Chile, specifically in the Coquimbo Region. For this type of research, Clark et. al., (2021) proposes the use of a representative case that captures the appropriate context to allow the researcher to answer the research question. By using a case study, it is possible to assess the drivers and barriers of multi-sectoral interaction according to the actual context, as this may vary according to location, even within a country. For example, the north of Chile has water scarcity problems and therefore desalination plants are presented as a drinking water supply option, but in the south of the country there are plenty of fresh water sources. Thus, the technical, economic, regulatory and social parameters may vary within a country.

To measure drivers and barriers of interactions between sectors, the description of concepts in the previous section were used to define indicators (see Table 1). These indicators are aligned with the MSD framework as they seek to measure the multiple mechanisms of interaction and the multiple dimensions of drivers and barriers. In the case of interactions, the indicators are the ways in which sectors can interact, i.e. resource flows, operational dependencies and feedback mechanisms. For drivers and barriers, the indicators will be the technical, economic, regulatory and social dimensions. The data collection was therefore focused on obtaining information on these concepts in each of their indicators in order to answer the research question.

Table 1: Operationalisation of concepts.

Concept	Definition	Indicator
Interaction	The ways in which different sectors, systems or actors influence each other.	Ways of interaction: • Resource flow • Operational dependencies • Feedback mechanisms
Barrier	Obstacle or challenge that hinders effective integration or collaboration between sectors.	Barrier dimension: • Technical • Economic • Regulatory • Social
Driver	Forces that promote or enable collaborations across sectors.	Driver dimension: • Technical • Economic • Regulatory • Social

3.2. Sampling strategy

As a primary source of information semi-structured interviews were conducted. This type of interview is one in which the interviewer has prepared an interview guide with a list of open-ended questions in advance, but the order or form of the questions may vary during the interview (Clark et. al., 2021). While all interviews were seeking to answer the research questions, the form and focus may vary somewhat depending on the interviewee. Annex 1 shows the interview guide used, in which the introductory questions were not asked in the same way for local residents because they do not represent an institution.

Interviewees were selected on a non-random basis, as purposive sampling seeks individuals who can provide information-rich responses for each sector. The participants were contacted via LinkedIn, email, phone calls and through contacts with relatives. In order to have access to interviewing different people in each sector, snowballing was subsequently used. This increases the total number to be sampled and make it easier to contact other actors in unfamiliar sectors (Clark et. al., 2021).

A total of 15 interviews were conducted with stakeholders from both industries and local residents (See Annex 2 for an overview of interviewees). Six interviews were conducted with industry actors, three in the water sector and three in the energy sector. Additionally, two interviewees are related to both sectors as they work in engineering companies developing industrial projects, both with experience in hydrogen and desalination. Three residents of the Coquimbo region were interviewed, but they fulfil a dual role because of their relationship with agriculture and the supply of materials for the development of industrial projects. To cover the regulatory area, two lawyers with expertise in water issues were interviewed. Finally, two academic researchers related to water, but also with hydrogen knowledge, were interviewed. Each interviewee was identified with a code to be referenced in subsequent sections, as shown in Annex 2 with an overview of the interviews.

The interviews were conducted in person or by videoconference, depending on the participant’s availability and preference. Each interview took from 30 to 50 minutes and were conducted in Spanish using a translated version of the interview guide from Annex 1.

Although the number of interviewees in each sector is not large, data saturation was reached as the last few interviews did not provide any new relevant information on the interaction between sectors. Nevertheless, these interviews provided new data that better explain the context of the water scarcity problem and the energy situation in the country. However, it was not possible to conduct interviews with people involved in the public sector, such as municipalities in the area, people in charge of the Ministry of Environment, Ministry of Civil Works, etc. These interviews could have provided important information on the interaction between sectors.

In addition to the interviews, desk research was conducted to corroborate some of the contextual data that contributed to the research without bias from the interviewees. For example, some interviewees claimed that there were actually 16 desalination plants in operation in Chile, while others said there were more than 20.

3.3. Data analysis

The online interviews were conducted via Teams, which has an automatic transcription tool that served as the basis for subsequent manual correction. For the in-person interviews, the audio was loaded into Microsoft Word with a transcription function. As with the online interviews, the automatic transcription was used as a basis and then corrected for errors.

Once all transcriptions had been corrected, the interviews were coded using NVivo software. Firstly, open coding was used to categorise the data with general labels, resulting in 63 codes.

Second order coding was then used to classify the information into 14 categories. Annex 3 contains a list of all first- and second-order codes along with the number of codes and the number of interviewees who referred to them. For example, “Hydrogen demand”, “Cost of desalinated water”, “Energy costs”, “Water source replacement” and “Human resources” were first order codes corresponding to the second-order code “Feedback mechanisms”. Secondly, thematic analysis was used to analyse the codes and compare them with previously defined concepts to make connections between information sources (Clark et. al., 2021). The coding and thematic analysis steps were carried out according to the operationalisation of the concept defined in Table 1. Through this analysis, it was possible to identify whether there are interactions between sectors, how they interact, and what are the drivers and barriers to interaction in order to achieve win-win collaboration. Therefore, the results of the data analysis consisted of a description of the potential ways in which the sectors could interact, the drivers and barriers in their four dimensions, and other conditions that could make collaboration more beneficial.

As the interviews were conducted in Spanish they were also transcribed in Spanish. However, the data analysis was conducted in English, which means that the names of the first and second order codes were defined in English and quotes directly used in the results were translated into English.

3.4. Ethics

In order to conduct the interviews in accordance with data protection legislation, participants were informed prior to the interview about the topic to be researched, how the information they provide will be used and stored, and the confidentiality of their personal data. A translated version of the consent form and information sheet in Annex 4, provided by the Department of Sustainable Development of Utrecht University, was used for this purpose. Once the participant signed the form, the interview was conducted anonymously and audio recorded for further analysis. The audios were deleted after the interviews were transcribed. The contact details of the interviewees were kept only by the author to send a copy of the final report.

4. Results

4.1. Multi-sector interactions

4.1.1. Resource flows

One of the main findings of the study was the existence of actual and potential resource flows between desalination plants and green hydrogen production. These flows were classified into 3 categories: water, energy and brine, as explained below:

Water

This physical resource is the clearest and most direct between sectors. The vast majority of respondents stated that green hydrogen production is highly dependent on a secure and abundant source of water for the electrolysis process [AW1; AW2; IE1; IE2; IH2; IH3; IW2; LW1; RO1]. As IH3 mentioned, “*the main output of one is the main input of the other one*” because, as IE1 stated, all the operational hydrogen plants and future projects require demineralised water, which is the output of a reverse osmosis process, and “*especially in the north of Chile, where these resources are scarce or more difficult to access, (hydrogen projects) are associated with desalination plants*” [IH3]. This has created a link between desalination plants and green hydrogen production, which has led to the integration of desalination plants into the hydrogen project or through strategic alliances.

For example, the Build-Operate-Transfer model was mentioned by IE1, where external companies build and operate the desalination plant and then sell the water to the hydrogen project for a period of time until the plant is owned by the energy producer. This alternative provides a long-term water supply and reduces the CAPEX of the hydrogen project.

A desalination plant could supply water to several sectors, such as drinking water utilities, agriculture, industry, etc. [LW1; IW2]. Green hydrogen producers are therefore seen as an additional customer for desalination plants. In this way, the benefits of providing such a vital resource as water can be shared with more sectors that also need it. As highlighted by LW1:

> “*In general, the desalination plants that are being built in Chile, at least starting with the Coquimbo plant, have a gigantic capacity that will probably not be required all year round. So, the extra that they produce can be sold to green hydrogen and generate truly green*

hydrogen, which comes from renewable energies that come from water, not inland water, but seawater.”

Energy

Another physical flow identified was energy, in terms of demand and possibility of energy exchange [AW1; AW2; IE1; IH1; IW1; IW2; LW1; RA1; RO1]. The desalination sector demands a high amount of energy for the reverse osmosis process and in order to transport seawater from the sea, brine back to the sea and desalinated water to the final user. On the other side, the process of electrolysis is energy intensive to split the molecules of water. Therefore, both sectors share a high demand for energy. Given this, some interviewees took this as a positive thing by bringing the two processes together with renewable energy sources, which in this case is not a flow of resources between sectors, but they do share the same resource flow in common with a third party [AW2; LW1; RA1]

Other interviewees went further thinking about an ideal scenario in which the green hydrogen could provide the necessary energy to operate the desalination plant as AW1 mentioned, “*I think that green hydrogen plants could provide, as we all hope, a kind of circular economy here, where green hydrogen provides enough energy to subsidise or, to finance the whole desalination process.*” This would reinforce the vision of green hydrogen as an energy carrier even within the system in which it is produced.

As shown in Figure 3, water and energy are the main resource flows between sectors, but they are not bidirectional. A desalination plant could provide desalinated water to several sectors, and green hydrogen could provide energy for others. The yellow dotted line could potentially be replaced by the energy produced from green hydrogen [LW1; RO1]. IE2 explains it in a positive way by highlighting:

“What we must be clear about is that Chile has a tremendous opportunity because we have 4,000 km of coastline and we have the highest renewable energy resources in the world in terms of wind energy and solar radiation for the production of photovoltaic energy. Therefore, it is clear that there is a gigantic opportunity to produce added value and produce wealth for the world and for the country based on this fortunate fact that we have a coastline and we have the energy resources to produce renewable energies.”

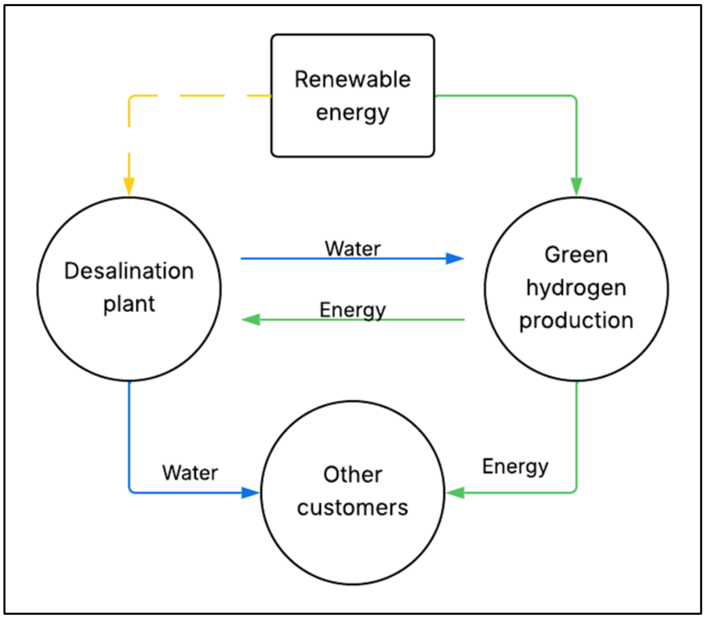

Figure 3: Water and energy resource flows.

Brine

Brine was mentioned by IW3 who briefly mentioned that this waste product has an important energy value because of all the concentrated minerals in the water. Although IW3 did not mention the use of brine for the electrolysis process or with the production of green hydrogen, he does mention that brine can be used by the energy sector. However, IW3 detailed that this connection is currently non-existent between the two sectors in the country, but that in the future it could lead to a development that adds value to waste and minimises environmental impacts.

4.1.2. Operational dependencies

In addition to resource flows, various forms of operational dependencies between the sectors studied were demonstrated. These dependencies refer to the shared use or pooling of structures and/or processes between sectors. Two categories of operational dependencies were the most prominent: infrastructure and external actors.

Infrastructure

Shared infrastructure was one of the most recurring forms of interaction between desalination and green hydrogen production. Some of the shared infrastructure between the sectors could include ports, roads, logistics and distribution, electrical grids, pipelines and industrial zones for their operation [IE1; IE2; IH1; IH2; IH3]. It was also suggested that ancillary areas could be shared, such as quality control systems or electrical installations, which could promote operational efficiency [IH2; IW1].

As mentioned in the previous section, several of the interviewees said that green hydrogen projects in Chile include within their design the development of desalination plants to supply water. In this way the desalination plant already becomes part of the energy project, and the electrolysis process is totally dependent on the desalination plant [IE1; IE2; IH3; IW2]. For example, AW2 mentioned "*I see the link within the same project. I have my mining project, I have my desalination plant, I have my hydrogen production*".

Additionally, some noted that the development of this type of industrial project can also have a positive impact on the creation of new infrastructure, as highlighted by IH2:

> *“In the south, for example, where there is no major industrial development, where there is no infrastructure of any kind, where there is also a road network that needs to be developed, the establishment of green hydrogen projects brings that as well, the development of infrastructure that is required for business”*

Finally, a key dependency for the functioning of both sectors is renewable energy. In the case of hydrogen, it must be renewable to be classified as green, while the desalination plant does not require renewable sources. However, it was commented that their environmental and economic viability may depend on the use of renewable energy [AW2; IW2; LW1]. This way IW2 highlighted that “*Energy as a major shared work. I would imagine that's a kind of major work that in today's worlds must be renewable*”.

External actors

An interesting angle that emerged from the analysis was the dependence on external actors, understood as industries or organisations other than the desalination and hydrogen sectors, but which play a key role in the functioning of the multi-sector system.

The mining sector was identified in multiple interviews as a key actor, for several reasons such as being the most important economic sector in the country, its high water and energy consumption, and its interest in decarbonisation [AW2; IH3]. In this sense, mining projects not only share infrastructure, but are also the major demanders of desalinated water at the national level [IH3]. According to Fuentealba Pizarro (2024) by March 2023 68% of the desalinated water in Chile was destined for the mining industry. In this way, the mining sector is presented as an entity that requires desalination and green hydrogen processes working together under the umbrella of a single project [AW2; IH3].

4.1.3. Feedback mechanisms

Unlike resource flows and operational dependencies, feedback mechanisms between sectors did not have many clear answers among participants. However, four possible feedback mechanisms were identified: hydrogen demand, desalinated water costs, human resources and water source replacement, detailed below.

Hydrogen demand

One of the positive feedback mechanisms is the effect of increased national or international hydrogen demand on desalinated water production [IE1; IH1; RA1]. As explained by IE1, hydrogen production requires a constant water supply, so "*if for example they need more hydrogen in Japan, the hydrogen plant and desalination plant has to grow".*

Desalinated water costs

The interviewees mentioned that the price of desalinated water is relatively high compared with other sources and given the unidirectional relationship of hydrogen production with the desalination plant, a negative feedback mechanism is generated in terms of costs [LW1]. Thus, interviewees highlighted that in the current scenario of using of desalinated water to produce hydrogen, the final price of hydrogen depends on the cost of desalinated water and as long as that cost is high, the energy carrier will remain expensive. However, this externality does not occur in the opposite direction, i.e. a variation in the cost of hydrogen does not change the cost of the desalination plant [LW1].

Human resources

One aspect mentioned is the training of specialised human capital. Although the production processes are different, in both cases they require professionals who are experts in the handling of industrial equipment. IH2 pointed out that the development of each of the projects separately will generate positive feedback in terms of training and development of new professionals. Therefore, in this case the feedback mechanism is bidirectional and also targets other industrial sectors by generating an impact on the labour market.

Water source replacement

Finally, two interviewees pointed to a different feedback mechanism that has to do with water source replacement. Desalination schemes in northern Chile aim to destress inland water sources and use desalinated water for different uses [IE2; RA2]. For example, RA2 said that increased desalination for human and industrial consumption would recharge the Puclaro dam, leaving more water for agricultural development, and the hydroelectric power plant could once again generate energy.

While this feedback mechanism is not directly related to green hydrogen production, it is related to the energy sector and could potentially be related to operating the electrolysis process with inland water.

In summary, the sectors interact mainly because of the hydrogen sector's dependence on water. This leads to water resource flows and in turn an operational dependency, since, as interviewees commented, hydrogen projects consider the construction of desalination plants as part of the project.

4.2. Drivers and Barriers for interaction

When interviewees were asked about possible drivers and barriers to interaction between sectors, they tended to focus on barriers rather than drivers. Therefore, they tended to wonder about the challenges of adapting the existing operations to an unknown innovation. For this reason, in the following section the barriers are presented first, followed by the drivers.

4.2.1. Technical

I. Barriers

Water quality and electrolysis

The most frequently repeated technical barrier relates to the quality of water required for hydrogen production by electrolysis [AW1; AW2; IE1; IE2; IH2; IH3; IW2]. Not only interviewees with a technical background mentioned that one of the challenges of electrolysis equipment to date is that they must use ultrapure water, so the thought of using brine is counterproductive. They commented that the main problem is due to accelerated deterioration of the membranes and corrosion of the metals that make up the electrolysers [IE1; IE2; IH2; IH3]. On this subject IE2 commented:

"All the hydrogen projects I have known, which are not few, all depend on having ultrapure water; basically, the electrolysis process requires a very high level of water purification. In fact, there are often double osmosis processes".

Water without minerals does not conduct electricity, but by using ultra-pure water, the necessary minerals can be added and controlled to make the electrolysis process more efficient and reduce the deterioration of the electrolyser components.

Industrial scalability

Some interviewees stated that they were aware of the advances in research on seawater electrolysis but pointed out that even this application is at a very early stage of technological maturity [AW2; IH2].

In addition, from the academic point of view AW2 commented that technological innovation processes similar to this one could take between 8 to 10 years. At the same time, the projected demand for hydrogen according to government plans is very high, which makes it even more difficult for innovations still at the research stage to play a role in meeting that demand [IH3].

Process integration and industrial safety

Another point mentioned as critical is the integration of material and operational flows between plants. Detailed process engineering is required to avoid problems with the operation of each of the units, such as constant flows, avoidance of cross-contamination and the safety standards of each industry [AW1; IH1; IW1]. Green hydrogen is a flammable fuel and therefore has strict safety measures to avoid risks, while the desalination plant has other important risks [IW1]. This difference in safety requirements requires non-compatible operating standards and significant physical separation [IH1; IW1].

It was noted that the barriers associated with integration and industrial safety may be lower if they are considered from the design stage of the entire infrastructure, but the barriers become higher in the case of intervening processes that are already operating [IH1; IW3].

II. Drivers

Waste revalorisation

One of the main technical drivers mentioned was the use of waste as an input for another industry. In this scenario, what several interviewees referred to as a “virtuous circle” occurs, in which one waste generates value in another industry [AW1; AW2; IW1; LW1; LW2]. Furthermore, it is estimated that brine production will increase in the future, as one AW2 commented:

"I am a firm believer that reverse osmosis brine should not be discharged into the sea, it is an opportunity, it is a resource. Chile appears to be one of the countries that generates the most brine, and this is going to become more widespread, and we are thinking that by 2030 we will have 50 desalination plants. So, brine generation is a reality today and it is going to become more widespread".

Academic research

Another technical driver mentioned was the progress in academic research in both sectors. While it was commented that research on seawater or brine electrolysis is in the early stages, at least there is some progress, which was seen as a positive starting point [IE2; IH2; IW2]. On desalination issues, it was commented that there is a substantial amount of research, demonstrating that there have been no negative effects on the marine ecosystems where desalination plants operate in Chile, and that research is focused on efficiency improvements [IE2].

Renewable energy sources

Finally, the potential for renewable energy production in the Coquimbo area was highlighted. Participants recognised that the area has the advantage of having one of the highest solar radiation levels in the world and coastal wind for the development of wind energy [AW1]. These conditions are presented as an impulse to operate both plants with renewable energies from the area and thus depend as little as possible on conventional energies [AW1; IE2].

At the same time, IH1 pointed out that Chile has the particularity that there are unpopulated areas in which little use can be made of the land, which does not generate value for the development of housing, industrial or agricultural projects, especially in the north of the country in the middle of the desert. IH2 exemplified this by saying:

"Let's say, in front of my house you could have 10 windmills, but nobody wants to put them there and I don't want to see them either, but in Chile there are many places where they won't obstruct. There are a lot of fields in the hills, which are useless, so I think Chile has a very, very big advantage".

4.2.2. Economic

I. Barriers

Regarding economic barriers, interviewees did not mention barriers that are related to the interaction as such, but to each industry separately. Each industry has its own economic barriers that need to be overcome, which means that interaction is limited, since one cannot take off without the other.

Costs of green hydrogen

One of the major economic challenges for the green hydrogen industry is the high cost of green hydrogen production, especially compared to conventional energy sources such as diesel and natural gas [IE2; RO1]. Several interviewees commented that while it is technically feasible to produce and use hydrogen in the country, it is not yet competitive in the energy market [IE2; IH2]. Even if the use of brine as an input could eventually reduce production costs, other factors were mentioned that increase the cost, such as transport, storage and conversion of hydrogen [IH2].

The high cost means that Chile does not seem to have a consolidated market for hydrogen [IE2; IH2]. It was commented that the projects are waiting for incentives to force the energy transition towards green hydrogen since, according to IE2 “*in general, all green hydrogen developers have a spirit of venture capital, waiting for offtakers to start appearing*”. IE2 also pointed out that:

> *“I would say that the main barrier to the development of green hydrogen is not the technological problem, but the commercial problem at the core, who are the offtakers? Who pays the cost of hydrogen, that hydrogen is an expensive fuel or energy supply.”.*

Another barrier discussed by the hydrogen industry is the high cost of electrolysers [IE1; IH2]. Current electrolyser technology using ultrapure water requires internal components made of expensive metals and, it was mentioned, in the case of using brine, even more special and expensive metals would have to be used [IE1; IH3]. This situation makes it more difficult to achieve economies of scale and makes investment in such projects considerably more expensive [IH3].

Cost of desalinated water

For the desalination sector the main economic barrier is the high price of desalinated water. Similar to the case of hydrogen, few industries are able to pay a high price per cubic metre of water [AW1; RA2]. It was highlighted that sectors such as mining or construction are probably the main clients of desalination plants, but other sectors such as agriculture are the most disadvantaged [AW1]. In this regard, RA2 said that the projects to be built in the area estimate a price of desalinated water at 1.5 USD/m^3, on which RA2 commented “*I believe that before that,* *production will end, that water will be used for agriculture at these values, at these values that are being considered today”.*

In addition, it was noted that these water prices directly influence actual hydrogen production, as they require ultrapure desalinated water as an input [IE2]. In turn, the cost of desalinated water is largely determined by the energy required in the production and transport process. Therefore, energy cost is the critical economic barrier for both sectors.

II. Drivers

Cost reduction

One of the most frequently mentioned points regarding economic drivers of interaction refers to the potential cost reduction overall [IH2; IH3; IW3]. IH3 commented that approximately 70% of the cost of hydrogen in Chile is associated with electricity and of the remaining 30%, water is an important part. On this point IH3 points out the industry challenge:

> *“What interests me is that, somehow, with a black box, I can get hydrogen at 2 or 3 USD. If I am able to get hydrogen at those prices, everything downstream becomes more interesting and profitable”.*

Therefore, if using brine reduces the cost of hydrogen associated with water, green hydrogen could potentially reach values that would make it competitive in the energy market [IE1; IH3; IW3; LW2]. This is based, as interviewees highlighted, on the efficiency and technical barriers associated with brine electrolysis being overcome.

Revalorisation of by-products

From the point of view of the business model, the possibility of valorising the by-products of both production processes was highlighted [IH2; IW1]. In particular, the valorisation of the chlorinated products formed in brine electrolysis opens up a whole new business branch for the manufacture of disinfectant products [IW1]. It was mentioned that even part of the disinfectant products can be used for the desalinated water purification process, which generates even more synergies between processes [IW1].

Local demand

Moreover, the growing demand for water throughout northern Chile was mentioned, which was seen as an economic driver [IE1; RA2; RO1]. RA2 pointed out that although desalinated water has a higher cost, drinking water is a guarantee that the state has to provide, and with water scarcity in the area, desalination is necessary. Therefore, the state will necessarily have to take measures to encourage private desalination projects or finance them itself to provide freshwater. This will also increase the amount of brine that will be potentially available for use in green hydrogen projects, which will facilitate economies of scale.

Carbon credits

Another source of economic incentive is the carbon credits associated with green hydrogen. Energy-intensive industries, such as mining, need to meet local and international requirements for their CO_2 emissions and carbon credits are a viable option to achieve this [IH1; IW3].

4.2.3. Regulatory

I. Barriers

Permit bureaucracy

Among all barriers and drivers in all dimensions, what was mentioned most often was the excessive bureaucracy in the processing of permits for project development. According to interviewees, the regulatory process in Chile is slow, complex, unfamiliar and with multiple entities involved [IE1; IE2; IW2; LW2; RA1; RO1]. An example was stated in which two government bodies discussed having responsibility for organising meetings for indigenous consultation [IE1]. In that discussion, 8 months of the project were lost in order to reach an agreement on which entity should organise the meeting, while the private party can do nothing about it. This makes it clear that these processes are unknown even to the public authorities themselves [IE1].

Of all the types of permits that need to be processed, environmental permits were the most criticised by interviewees. They commented that these permits are excessive and that the state has taken a negative bias towards the development of any type of industrial project that has to go through environmental assessment [AW1; IE1; IE2; IW1; IW2; LW1; LW2; RA1; RO1]. Projects such as the desalination plants for drinking water in Coquimbo have been delayed by the environmental permits while part of the population receives drinking water by truck twice a week [AW1]. On this issue, RA1 commented *“We have to define who comes first, the environment or human beings”*. This has led to a significant delay in the operation of projects, which was commented on by several interviewees [IE1; IW2; RO1]. IW2 commented from experience in the environmental processing of a desalination plant:

> *“When according to regulations it takes 1 to 2 years for an EIA (Environmental Impact Assessment), this is not the case today. Investors are faced with environmental regulations that take 10 years. The plant I was at took 10 years to get its environmental permit. This is also where other types of permits come into play, such as maritime concessions, which are supposed to be granted in four months, but in reality, they are being granted in three to four years”*

This excessive bureaucracy has discouraged investment in the country due to regulatory uncertainty [IE1; IW2]. Experiences were highlighted where companies with projects ready to operate and committed clients decided to move operations to other South American countries, due to shorter approval times. On this issue IE1 commented:

> *"Today we are not attractive, we are not growing, we are hindering and it is not about doing things badly. It is about doing things much better, much more efficiently and well, and we are not doing that and we are losing capacity".*

Other specific regulatory barriers affecting the integration between desalination and hydrogen were also mentioned. For example, there is no regulation governing easements to transport water or hydrogen, forcing project developers to negotiate directly with multiple landowners in order to install pipelines on their properties [IE2]. This can significantly delay projects and increase costs.

Politics

Interviewees also expressed that project development is strongly conditioned by the political context [AW1; IE1; IH3; RA1]. On this subject IE1 stated “*it depends on the government of the day and the shareholders whose side they are on, and this is noticeable*.” The absence of a stable and reliable institutional setting that can establish long-term policies is perceived [RA1], as it is difficult to predict what the political environment will be like in five years' time [IH3].

In Chile, presidents lead the country for a period of four years, and since 2006, Chile has alternated between left-wing and right-wing governments. This has meant that certain issues have not been pursued consistently over the last two decades. A clear example of this was the controversy surrounding the constitutional reform proposed by a left-wing government and then set aside by the right-wing government that followed (Ossa et. al, 2023).

Desalination regulation

Currently, desalination does not have a specific regulatory framework in Chile, which represents a regulatory barrier [IW2; IW3; LW1]. It was commented that, in order to process this type of project, developers must adapt to the use of regulations from other sectors or even countries such as Australia, which has specific regulations for desalination plants [IW2]. It was also mentioned that there is no regulation on brine management in the country [AW2; IW3]. AW2 pointed out that this discourages innovation, because if there were a regulation that requires you to treat this waste, there would be an incentive to look for solutions. Furthermore, the lack of regulation may create a problem in the future, as the project developer does not know whether they will encounter problems in the future.

Water ownership

Chile has a regulatory framework for water ownership through water rights [LW2; RA2]. However, there is legal uncertainty over the ownership of desalinated water and its by-products, as commented by LW2:

> *“The use of seawater as a resource is not regulated, i.e. anyone can extract water from the sea and it is not subject, for example, to concessions for the right to use it, but only to a concession to occupy what is legally understood to be the beach”*

This uncertainty represents a barrier that may hinder the transfer of brine to the green hydrogen plant, not only from a regulatory point of view, but also in terms of the structure of the business model [RA2].

II. Drivers

Although specific regulatory frameworks for integration between plants do not yet exist, some interviewees pointed out that the technical interaction between desalination and green hydrogen plants does not present major legal barriers, but also no major drivers.

Decarbonisation and reduced water footprint

The only relevant regulatory driver identified is the commitment to decarbonisation, which is putting pressure on various industries to reduce their emissions [AW2; LW2]. Some of the examples that were discussed are initiatives by the IMO (International Maritime Organization) and ICAO (International Civil Aviation Organization) to reduce the use of fossil fuels and that point to hydrogen as an alternative [IH1]. For the desalination sector, there are new regulations restricting the use of continental water for mining, leaving desalination as one of the only viable options for the industry [IW2].

Although decarbonisation and measures to reduce the water footprint are not specific to cross-sector interaction, both benefit from these regulations. A single project that can contribute to both regulations is much more robust than others that only seek to decarbonise or reduce the carbon footprint.

4.2.4. Social

I. Barriers

Community resistance

One of the most recurrent social barriers was the resistance of local communities to any kind of industrial projects. Over the last few years, this opposition has become widespread in Chile, where communities, including artisanal fishermen, residents and environmental organisations, are distrustful of private companies, especially due to the environmental effects of such initiatives [IE2; IW2; IW2, LW1; RA1; RO1].

One of the groups that were perceived as most affected by this type of project are the artisanal fishermen, as they emphasise that if a desalination plant is installed, they will lose their raw material [IW3]. However, IW1 pointed out that it is these same communities that are demanding a solution in order to have a supply of drinking water. This conflict is not specific to the Coquimbo region, as this has also been witnessed in Magallanes with the large green hydrogen projects [IE2].

In addition, it was highlighted that this barrier is very complex to resolve, because it does not depend on technical or economic issues, as AW1 commented *"there is a part of society that is against (industrial projects)"*. On this issue, IE2 with his experience in project development commented *"it is a problem that is difficult to solve, it is not only a matter of economic compensation, it is a much more complex and deeper issue".*

The citizen consultation process is part of the environmental processing process, which allows people to make observations, give their opinions and express concerns about projects that may impact their environment (Ortiz Hidalgo, 2020). RO1 participated in the citizen consultation of a desalination project in Coquimbo, about which he highlighted the ease with which a demand can paralyse a project, commenting:

> *"The community got together, grabbed a minimum amount of vegetation (that could be affected by the project) and raised it to a high power to make demands (...). They should have been building by now, but permits and communities have been major barriers"*

In addition to citizen consultations, projects must go through an indigenous consultation process, which aims to engage indigenous and tribal peoples to express their concerns about projects that affect their ancestral traditions, religious practices or relationship with their lands (Leppe Guzmán, 2015). This process was also commented as an important barrier to the development of any industrial project [AW1; IE1; LW1; RA2]. In the case of Coquimbo, RA2 commented that the coastal area belonged to the Changos, who have previously opposed desalination projects in the area.

The development of industrial projects can also generate conflicts with communities over land use and the displacement of communities, especially those who make a living from agriculture [IH1; RO1]. The installation of all project-related infrastructure such as solar farms, wind turbines and roads can compete with land currently used for agribusiness. This may generate a significant loss of jobs in the area threatening communities to migrate [IH1; RO1].

Environmental impacts

Another significant social barrier relates to the fear of possible environmental impacts and how these affect individuals [RA1; RA2; RO1; LW2]. Some of the points that were mentioned were the increase in water consumption from hydrogen projects, especially when there are scarcity [IH1] and secondary effects on the sea from desalinated water production and port infrastructure [LW2; RA2; RO1]. Also, IH3 mentioned indirect effects such as light pollution that can affect astronomical sites and which is currently holding up a project. These examples reflect that there is a highly sensitive environment, in which environmental impacts are perceived as social barriers.

Lack of knowledge

Finally, a transversal social barrier not only for desalination and hydrogen projects is the lack of knowledge and misinformation [AW1; IE2; IH2]. As an example of this barrier IE2 commented that there are many myths about the side effects of desalination plants, while AW1 acknowledged that this phenomenon even affects the academic sector as there are still gaps between disciplines and little exchange of information. It was highlighted that the problem stems from a lack of information campaigns and early engagement with communities, leading to mistrust [IH2].

II. Drivers

New water sources

The urgent need for water in the Coquimbo region was mentioned as a key social driver [AW1; AW2; IH2; IW3; LW2; RO1]. Although it was mentioned earlier that there is resistance to industrial projects, even when communities benefit from them, an important part of the community positively values projects that ensure water supply [IE2; LW2]. Furthermore, the agricultural sector in the area is one of the most interested in access to other water sources [IE1], not only to continue with their economic activity, but also for the entire population linked to these activities and who make a living from them [LW2].

Reduce environmental impacts

The possibility that collaboration between desalination plants and green hydrogen can help reduce or mitigate environmental impacts was another social driver mentioned. Mainly mentioned was the reduction of brine discharge into the sea, which could reduce the resistance from communities [AW2; IW3; LW1; RO1].

In addition, it was highlighted that it is possible to improve the quality of life of communities where projects are installed [IH2]. For example, IE2 commented that if green hydrogen can be introduced in mining, it would reduce CO_2 emissions into the environment, which brings health benefits.

Employment generation

Finally, the generation of local employment was mentioned as a key benefit for communities [IE2; IH2; LW1]. Project development generally activates other associated businesses that generate positive impacts on local economies, generating new jobs that are not directly related to the project [IE2].

4.3. Conditions for enhanced interaction

The interviews identified a number of conditions or factors that could strengthen the interaction between the desalination industry and green hydrogen production. In contrast to the drivers described in the previous section, these conditions are things that do not yet exist or could be enhanced to counteract barriers. Furthermore, they aim to generate new opportunities to capitalise on cross-sectoral collaboration. The conditions discussed by the interviewees are presented below.

Coordination between sectors

One of the factors mentioned is effective coordination between the sectors involved throughout the project lifecycle [IH1; IH3; RA2]. It was mentioned that many projects fail because each sector acts in isolation, prioritising its own business [RA1], about which IH3 highlighted “*collaboration and coordination and synergy between these sectors is key to determine and be able to make viable projects that are so large”.*

There are different ways in which there can be coordination between sectors and one way that was mentioned was Swap contracts [LW1]. LW1 detailed that this type of contract is used in various industries for the supply of resources as it allows for collaboration between sectors through a third party.

The need for coordination from the beginning with a long-term vision was also mentioned. For example, IH1 mentioned that in the planning phase, construction should be coordinated in stages with the possibility of expansion. In this way, the mitigation of environmental and social impacts is considered from the beginning with a higher production than the initial one, thus avoiding, for example, the displacement of communities due to space requirements.

Research

Research was named as an important pillar for the development of innovative and socially beneficial technical solutions. According to Ahmed et. al (2022) academia serves the industry by training professionals to run the industry and conducting studies that can be used to develop innovations, therefore, collaboration between both sectors is desirable. The link between academia, society and industry is something that needs to be strengthened to generate circular economies, as mentioned by IW1. Academic research can provide tools to improve industrial processes [IW2] and technically validate the use of by-products such as brine [LW2; RA2]. However, IW1 commented that academia and industry isolate themselves with an “I research” vs. “I produce” isolation, which needs to be put aside to benefit all sectors.

Regulation

The need for regulation was also identified in each sector separately and jointly to facilitate cross-sectoral collaboration [LW1]. In this theme they refer to regulations that incentivise innovation for example in terms of waste disposal [AW2; IW3] and avoid restrictive regulations, such as a possible regulation of hydrogen production technology [IH3]. This would give way to research and development around the circular economy [AW2].

The urgency of simplifying the excessive bureaucracy that currently slows down many projects was mentioned [IE1; IW2]. This includes optimising environmental assessment times and ensuring that there is clarification of the responsible public bodies [IE1]. In this way, environmental processing times could be shortened and foreign investment in industrial projects could be attracted [IW2].

In addition some interviewees pointed out that a strong and stable public policy is fundamental to advance projects that combine strategic sectors [IE2; IW2; RA1]. It was commented that collaboration between sectors must be backed by a state vision, as RA1 highlights: “*As water and electricity are indispensable for life, the state has to commit itself. I can't leave it to the private sector*”. Examples from the past were shared, such as the rapid implementation of natural gas terminals after the Argentinean gas crisis, demonstrating that when there is political will, big projects move fast [IE2].

External communication

Finally, one of the most widely mentioned conditions for improving multi-sectoral interaction was the need for effective communication with communities and stakeholders. Several interviewees pointed out that social conflicts are exacerbated by a general lack of knowledge about the project [AW2; IW2; RA1].

It was emphasised that environmental education and early engagement can transform communities from opponents into potential allies for project development [AW2; IH2; IW1]. In the process of educating communities, transparency on environmental impacts and demonstrating the benefits that the project generates for them, such as renewable energy generation and long-term safe water supply, was highlighted [IW1; IW2; LW2]. Regarding community participation, communities must be involved from the beginning and the flow of information must be continuously transmitted [IW1; IW2].

5. Discussion

5.1. Theoretical Implications

This research contributed to the development of the literature on Multi-sector Dynamics (MSD) by applying the framework to an emerging and relatively unexplored interaction between the desalination and green hydrogen sectors. The findings provided theoretical insights into how the application of MSD can be used not only to analyse existing interdependencies but also to discover potential synergies in contexts where collaborations are still in the formative stage. Specifically, the study demonstrates how interactions between sectors can occur through resource flows, operational dependencies, and feedback mechanisms.

One of the theoretical contributions is the identification of a unidirectional interdependence, in which green hydrogen is highly dependent on desalination, but desalination does not depend on green hydrogen production. The desalination sector can have multiple customers, of which hydrogen production is only one of them. These findings challenge interpretations of “win-win” collaborations and suggest that synergies between sectors may be unequal, but still important to analyse.

The study revealed that feedback mechanisms, one of the key mechanisms of interaction, are not always present or easily detectable in the early stages of collaboration. Although some feedback mechanisms were observed, these were limited compared to resource flows and operational dependencies. This suggests that MSD could benefit from a phased conceptualisation, in which, depending on the level of maturity of the multi-sectoral system, different interaction mechanisms are more or less dominant. The existing literature on MSD does not emphasise the different stages in which sectors interact, and this is a key issue to consider when studying these systems.

This study analysed two sectors that are in their early stages, but there are sectors that have been collaborating for a long time, such as water and agriculture. Depending on the stage of these relationships between sectors, the dynamics may be different. For example, in the early stages, there may not be a high level of trust between sectors, as they have not yet managed to obtain significant benefits from this collaboration, and there may even be investment without return. In mature collaborations, however, efforts may be focused on improving efficiencies for both parties.

For this reason, the framework could be more useful if it distinguished between the different stages of collaboration and how to approach them.

5.2. Limitations

Theoretical Limitations

The MSD framework, which is still in the development stages, provides a robust structure for analysing sectoral interactions, but it still has some limitations. One of the biggest limitations in this study was the significant influence of sectors outside the scope of the study. In this case, the mining sector was mentioned on several occasions, as it is a very important economic sector in the country, which in turn requires large amounts of water and energy to operate. To a lesser extent, the agricultural sector was mentioned as a possible competitor to hydrogen in terms of the water resource provided by desalination. In strict terms, all sectors could be considered part of a system since they are directly or indirectly related at the country, continent or global level. However, MSD, like other theoretical frameworks such as MLP, does not define how to establish the boundaries of the system in order to analyse it, as MSD does not contain a defined mechanism for incorporating other sectors that are not part of the system to be analysed but are highly influential.

In general, setting boundaries is challenging in different types of studies. In the case of MSD, the first step could be to analyse the sectors at a general level, understanding who the stakeholders are in order to gain an overview of the interactions. Once this has been scanned, the study can focus on the specific interaction that is to be analysed. In this way, it is possible to know in advance which third parties may influence the interaction and, for example, design the study methodology so that these sectors are also interviewed.

Methodological Limitations

The study consisted of 15 interviews with different stakeholders, evenly distributed between both sectors. Although it was determined that data saturation was achieved with the types of people interviewed, no interviews were conducted with public entities or representatives of indigenous peoples, which could have provided new information. In Chile, there is a formal mechanism, called the Lobbying Law, which is used to request a meeting or interview with any public employee and is legally the only way to contact them. This mechanism was used to request interviews with people working in municipalities in the Coquimbo Region, Ministry of Energy, Ministry of Civil Works and Ministry of the Environment, but no response was received. Attempts were also made to contact the Changos community, but there were no responses either.

During the research, the snowball methodology was used to find new participants for the interviews. This may have led the interviewees to think similarly about certain issues, which could have biased the information provided. For example, several of the interviewees clearly had strong political views that influenced their responses.

Furthermore, the interviews were conducted in Spanish and then analysed in English, which may have led to minor changes in translation or minor changes in meaning, especially in cultural expressions specific to the country. However, given that the author is Chilean, cultural expressions were correctly understood and translated into English in a way that was not literal, but rather conveyed the real meaning, which does not invalidate the results of this study.

Limitations of Generalizability

This study was conducted using a single case study in the Coquimbo Region of Chile, given the context of water scarcity and energy transition. However, it is not the only place in the world with these characteristics. Social, political, and environmental contexts vary depending on the location being studied, so the results of this study cannot be completely generalised to other regions of Chile or internationally. Many of the technical and economic drivers and barriers can be generalised, as they tend to be more independent of the physical location, while regulatory and social dimensions do depend on context. For example, the problem with Chile's extreme bureaucracy may not exist in other parts of the world or may be even worse, or indigenous peoples in an area may have less or more participation in the development of industrial projects and may be for or against them.

It is also important to note that the interactions and their drivers and barriers are prospective, i.e. not a consolidated reality. This means that the study identified potential interactions and is based on what the interviewees envisaged as possible drivers and barriers. Thus, the results should not be generalised without prior interpretation if they are to be used for decision-making.

5.3. Recommendations

Based on the study's findings, several recommendations can be made to industry players, policymakers, and other decision-makers to achieve successful multisectoral collaboration between desalination and green hydrogen in Chile. The recommendations aim to overcome barriers and leverage drivers of interaction.

From the perspective of industry actors, one of the recommendations is the integration of processes from the planning and design stages. This can contribute to reducing duplicate infrastructure, reducing future investment costs, achieving greater operational efficiency, and accelerating permit acquisition processes, especially environmental ones. At this early stage, the possible future expansion of operations for both processes should also be considered.

Furthermore, the production of valuable by-products for the chemical industry is something that deserves study, as it presents a potential economic opportunity in line with the principles of the circular economy. There are currently economically profitable companies in the chemical industry that use the saltwater electrolysis process to produce chlorinated products (Powthong, P. 2022). Therefore, the cost of green hydrogen could decrease by allocating costs across two products and eventually reach attractive values for the energy industry, which is its greatest challenge.

On the other hand, industry players must focus on building a good relationship with the community. This is achieved through a transparent and consistent communication plan throughout the project to establish a two-way communication mechanism. This will enable the company to communicate its news, employment opportunities and other issues, but also allow communities to express their concerns, be truly heard and enable the company to respond to these issues. All of the above are mechanisms that can serve to reduce resistance to projects from interested groups, such as artisanal fishermen, indigenous communities, local residents and other industries that may be affected.

In terms of public policy and regulations, the first priority is to create a regulatory framework for desalination and hydrogen production that is specific to the country, rather than based on regulations from other countries. Interviews with experts revealed that some of the key elements that these regulations should contain are definitions of water rights (sea water, desalinated water and brine) and the transport of resources (pipelines). It would also be beneficial to create policies that promote innovation, such as the integration of processes between industries.

In addition, work should be done to simplify the environmental impact assessment processes for projects. This could trigger a series of actions, as it will not only reduce the delays but also attract greater investment, thereby potentially increasing research for the development of innovations.

6. Conclusion

This thesis explored the potential synergies between the desalination and green hydrogen production sectors in the Coquimbo Region, as these are key sectors for Chile's sustainable transition. Specifically, the study focused on answering two research questions: (1) *How do the desalination and hydrogen production sectors interact in Chile?* and (2) *What are the drivers and barriers for a successful multi-sector system between desalination and hydrogen production to achieve a mutually beneficial collaboration in Chile?* To answer these questions, the study consisted of qualitative research based on the Multi-sector Dynamics framework. To this end, interviews were conducted with various stakeholders, including actors from each industry, academics, legal experts, and residents.

The findings showed that, although there is no fully developed multi-sector system, there are currently certain interactions between them, based mainly on the flow of water between desalination plants and green hydrogen production plants. Respondents commented that the country's green hydrogen plant projects include a small desalination plant to supply ultra-pure water for the electrolysis process. However, the relationship is unidirectional, as desalination plants do not receive resource flows from hydrogen production. Nevertheless, this interaction occurs within the umbrella of the same project, for example, a mining project that has its own hydrogen production plant and desalination plant, but it does not occur between independent sectors. With all this information, it was possible to answer the study's first research question.

In addition to identifying the current way in which sectors interact, the findings revealed other ways in which sectors could potentially interact. For example, the energy generated by hydrogen could (technically) be used to operate the desalination plant, which was proposed by interviewees as a possible resource flow. Certain operational dependencies and feedback mechanisms that could occur between sectors were also presented, although the latter mechanism was not as easily recognised by the interviewees.

Regarding interactions between sectors considering the use of brine in hydrogen production, barriers were mentioned such as the sensitivity of the electrolysis process, the high costs of producing desalinated water and hydrogen, an environmental assessment classified as excessive, and resistance from communities due to, for example, fear of potential environmental impacts.

However, interviewees also mentioned drivers such as the revaluation of waste, the potential reduction in the costs of desalinated water and hydrogen, regulations that seek to reduce environmental impacts in other industries, and the creation of new jobs. Thus, answering the second research question of this thesis.

In this case, the MSD framework proved useful not only for identifying technical or economic opportunities and challenges, but also regulatory and social issues that go beyond analysing a traditional business model or innovations.

The main conclusion of this thesis is that a mutually beneficial relationship between the desalination and green hydrogen production sectors in Coquimbo can be achieved and is desirable in order to address problems such as water scarcity and the sustainable energy transition. However, this collaboration requires commitment from both sectors, investment in further research, pilot testing, and specific actions to resolve the challenges that have been identified and those yet to be discovered. In this way, this thesis serves industry actors in each sector and public figures as a guide for decision-making that requires interaction between sectors to achieve the development of sustainable innovations.

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8. Annexes

8.1. Annex 1: Interview guide

Introduction and background questions

1. How does your organization contribute to the water or energy sector?
2. Can you tell me about your role and responsibilities within your organization?

Sectoral involvement

3. What is your organization's involvement or interest in desalination or green hydrogen production? And how are you involved on those activities?

Interactions

There are different ways in which sectors can interact. These can be grouped into three broad categories, which are resource flows, operational dependencies and feedback mechanisms.

   a. Resource flow refers to the exchange of physical, financial and/or knowledge resources between two or more institutions.
   b. Operational dependencies Operational dependencies occur when sectors share processes or infrastructure, creating dependencies between them.
   c. Feedback mechanisms occur when a change in one sector creates a benefit or challenge in the other.

4. What could be potential resource flows between desalination plants and green hydrogen production?
5. What could be potential operational dependencies between desalination plants and green hydrogen production?
6. What could be potential feedback mechanisms between desalination plants and green hydrogen production?
7. Can you provide examples where a collaboration with the other sector has been successful and challenging?

Drivers and barriers

Now let's consider a possible collaboration between desalination plants and green hydrogen production, using brine as the main input for electrolysis in the Coquimbo region. This region has water stress problems, and the government has already announced tenders for desalination plants. In parallel, the region has great potential for solar and wind energy production and Chile's decarbonisation plans include a Green Hydrogen Action Plan, in which green hydrogen is projected to account for 16–18% of national energy consumption. In the context of this collaboration,

8. What are the technical drivers and barriers for interaction between desalination and hydrogen production?
9. What are the economic drivers and barriers for interaction between desalination and hydrogen production?
10. What are the regulatory drivers and barriers for interaction between desalination and hydrogen production?
11. What are the social drivers and barriers for interaction between desalination and hydrogen production?
12. What factors or conditions would make the collaboration between sectors more beneficial?
13. What other potential synergies could arise from closer integration between desalination and hydrogen production?
14. Do you have any additional thoughts about the desalination and hydrogen sectors you would like to add?

8.2. Annex 2: Overview interviews

Number	Code	Actor type	Date interview	Interviewee's role
1	IW1	Industry - Water	12-02-2025	R&D
2	RA1	Resident - Agriculture	25-02-2025	President of the Northern Agricultural Association
3	RA2	Resident - Agriculture	26-02-2025	Manager of Elqui River Surveillance Committee
4	IW2	Industry - Water	26-02-2025	Sustainability manager
5	IE1	Industry - Engineering	28-02-2025	Decarbonisation Leader Chile
6	IH1	Industry - Hydrogen	28-02-2025	Consultant
7	IW3	Industry - Water	28-02-2025	Researcher
8	LW1	Lawyer - Water	03-03-2025	Lawyer
9	IE2	Industry - Engineering	04-03-2025	CEO
10	LW2	Lawyer - Water	04-03-2025	Lawyer
11	AW1	Academic - Water	06-03-2025	Researcher
12	RO1	Resident - Other	07-03-2025	CEO of industrial piping supplier company
13	IH2	Industry - Hydrogen	21-03-2025	Hydrogen director & Member of H2 Chile
14	IH3	Industry - Hydrogen	25-03-2025	Green hydrogen business developer
15	AW2	Academic - Water	27-03-2025	Deputy director - researcher

8.3. Annex 3: Codes

Second order code	First order code	Number of codes	Interviewees
Problem context	Problem context	43	12
Resource flows	Water	18	9
	Energy	11	9
	Brine	1	1
	Knowledge	1	1
Operational dependencies	Infrastructure	16	9
	Third parties	4	4
	Renewable energy production	3	3
Feedback mechanisms	Hydrogen demand	3	3
	Cost of desalinated water	2	1
	Energy cost	2	2
	Water source replacement	2	2
	Human resources	1	1
Technical driver	Use of waste	11	6
	Renewable energy sources	4	3
	Academic research	3	3
	Resource transport	1	1
Technical barrier	Brine electrolysis	18	7
	Industrial effectiveness	8	3
	Process integration	7	4
	Renewable energy sources	7	4
	Industrial safety	4	2
	Other technical barriers	4	3
	Quality of products	2	2
Economic driver	Reduce CAPEX - OPEX	9	6
	CO2 credits	3	2
	Demand for water	3	3
	Local energy demand	1	1
Economic barrier	Cost of H2	9	3
	Cost of desalinated water	8	3
	Clients	4	2
	Electrolysis	4	3
	CAPEX	3	2
	Industrial feasibility	3	2
	Regulations	2	1
Economic uncertainty	Economic model	5	3
Regulatory driver	Decarbonisation	5	4
	Process integration	4	2
	Simplifying bureaucracy	2	2

Regulatory barrier	Permit bureaucracy	31	9
	Desalination regulation	10	5
	Hydrogen regulation	5	5
	Other regulations	5	3
	Politics	5	4
	Water Ownership	5	2
Social driver	New source of water	10	8
	Reduce environmental impacts	8	8
	Renewable energy	4	4
	New jobs	3	3
	Utilization of empty land	2	1
Social barrier	Community resistance	13	8
	Environmental impacts	10	7
	Displacement of communities	5	2
	Indigenous people	5	4
	Lack of knowledge	5	4
Conditions for a better interaction	External communication	9	6
	Coordination	8	5
	Regulations	5	4
	Research	5	4
	Politics	4	3
	Mining	2	2
	Shareholders' initiative	2	1
	Simplifying bureaucracy	2	2

8.4. Annex 4: Consent form and information sheet

INFORMED CONSENT FORM (INTERVIEW)

In this study we want to learn about multisector dynamics that occurred in the potential collaboration between desalination plants and green hydrogen production. Participation in this interview is voluntary and you can quit the interview at any time without giving a reason and without penalty. Your answers to the questions will be shared with the research team. We will process your personal data confidentially and in accordance with data protection legislation (the General Data Protection Regulation and Personal Data Act). Please respond to the questions honestly and feel free to say or write anything you like.

Everything you say or write will be confidential, and anonymous. This means that we do not ask for your name, and no one will know which respondent said what.

I confirm that:

- I am satisfied with the received information about the research;
- I have no further questions about the research at this moment;
- I had the opportunity to think carefully about participating in the study;
- I will give an honest answer to the questions asked.

I agree that:

- the data to be collected will be obtained and stored for scientific purposes;
- the collected, completely anonymous, research data can be shared and re-used by scientists to answer other research questions;

I understand that:

- I have the right to see the research report afterwards.

Do you agree to participate? o Yes o No

INFORMATION SHEET (INTERVIEW)

INTRODUCTION

The purpose of the study is to learn about the opportunities and challenges of a collaboration between desalination plants and hydrogen production in Coquimbo, Chile. The study is conducted by José Tomás Ovalle who is a student in the Msc programme Sustainable Business and Innovation at the Department of Sustainable Development, Utrecht University. The study is supervised by Adriaan van der Loos.

PARTICIPATION

Your participation in this interview is completely voluntary. You can quit at any time without providing any reason and without any penalty. Your contribution to the study is very valuable to us and we greatly appreciate your time taken to complete this interview. We estimate that it will take approximately 30 minutes to complete the interview. The questions will be read out to you by the interviewer. Some of the questions require little time to complete, while other questions might need more careful consideration. Please feel free to skip questions you do not feel comfortable answering. You can also ask the interviewer to clarify or explain questions you find unclear before providing an answer. Your answers will be noted by the interviewer in an answer template. The data you provide will be used for writing a Master thesis report and may be used for other scientific purposes such as a publication in a scientific journal or presentation at academic conferences. Only patterns in the data will be reported through these outlets. Your individual responses will not be presented or published.

DATA PROTECTION

The interview is also audio taped for transcription purposes. The audio recordings will be available to the Master student and academic supervisors. We will process your data confidentially and in accordance with data protection legislation (the General Data Protection Regulation and Personal Data Act).

Audio recordings will be deleted when data collection is finalized, and all interviews have been transcribed.

Everything you say in this interview will be confidential and completely anonymous. This means that we will not ask for your name, date of birth, or other personal information that can be traced to you by us or a third party]. We will process your data confidentially and in accordance with data protection legislation (the General Data Protection Regulation and Personal Data Act)