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SOCIAL AND ECOLOGICAL EFFECTS OF RECYCLED WATER AND SEAWATER DESALINATION IN A GREEN HYDROGEN HUB: a comparative Systems Dynamics study

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1. Introduction

Climate change impacts various aspects of the climate system and holds substantial implications for the biosphere and socioeconomic development (Intergovernmental Panel on Climate Change, 2012, 2022). Predominantly caused by the combustion of fossil fuels and the emission of greenhouse gases, a critical solution lies in enhancing energy efficiency and transitioning to cleaner energy sources (York & Bell, 2019). Green hydrogen (GH) emerges as a promising clean energy carrier, offering a potential leap in the energy transition and sustainable development (Abad & Dodds, 2020; Ginsberg et al., 2022).

Several Brazilian states are signing Memorandum of Understanding with potential hydrogen companies, particularly in the northeast. Ceará is pioneering a GH production and export hub supported by its substantial renewable energy production and the existing Pecém Industrial and Port Complex (CIPP) (Garlet et al., 2024). The CIPP, located in the Metropolitan Region of Fortaleza (MRF), includes an industrial area, port, and export processing zone, with a robust electric network and favourable fiscal conditions for a GH hub (Complexo do Pecém, 2024). Despite plenty of renewable energy resources, water scarcity in Ceará poses a significant challenge, for the population that requires freshwater as well as the incoming hydrogen production that requires high-purity water (Souza Filho, 2018). A better in-depth comprehension of water resources is crucial for GH production, especially in semi-arid regions with hydrogen potential, which are likely to be severely affected by climate change (Ceará, 2019; European Commission, 2020; Shi et al., 2020). Challenges related to climate, and abuse of water resources can further unbalance water availability, exacerbating existing vulnerabilities and potentially creating new ones (Hermesmann & Müller, 2022; Woods et al., 2022).

Droughts are a recurrent problem in Ceará, often causing water conflicts, particularly in the Castanhão region, home to the state's largest reservoir. Water reallocation from Castanhão to the Metropolitan Region of Fortaleza (MRF) for human and industrial use, including the CIPP, has led to frequent disputes over water management, tariffs, and allocation (Studart et al., 2021). Simulations for the Castanhão-Metropolitan water system indicate significant future water stress, especially during droughts, potentially leading to systemic collapse (Silva et al., 2019). In the sight of the challenge of insufficient reservoir water for the CIPP to run operations of the forthcoming hydrogen industry, and to shed light on the literature's gap about what are the implications of hydrogen operations people living in semi-arid regions (Almaraz et al., 2024; Blohm & Dettner, 2023; Dillman & Heinonen, 2023; Müller et al., 2022), this study aims to evaluate the production of green hydrogen comparing the use of two different water sources: recycled water, representing a circular economy approach, and seawater desalination, representing a linear economy approach. This research contributes to the literature on circular economy practices in renewable energy production by applying the system dynamics framework to assess the viability and sustainability of these water resources.

2. Theoretical background

2.1. GH and water consumption

Hydrogen can be obtained by various methods, including water electrolysis. Water electrolysis is prominent in GH production because it does emit low levels of greenhouse gases when using renewable energy, however, it is costly than the other alternatives (Abdin et al., 2020). Despite high costs with energy demand, electrolysis becomes viable with ongoing decreasing renewable energy costs, indicating a trend towards affordability and sustainability for GH (Macedo & Peyerl, 2022; Zhou et al., 2022). Nonetheless, to achieve economically viable GH, addressing challenges such as technological advancements and reducing the high transportation costs are necessary alongside new policy developments (Beswick et al., 2021; Garlet et al., 2024; Shi et al., 2020).

Managing water consumption in the GH industry is as challenging as managing energy consumption, with significant long-term impacts on ecosystems and local water availability (Hermesmann & Müller, 2022). Water is essential in GH production for splitting the water molecule and for cooling operations, including the production of ammonia (Australia, 2022; MacFarlane et al., 2020). Water-to-hydrogen production ratios range from 10 to 22.4 kg of water per kg of hydrogen, with a total water footprint up to 43 litters per kg of GH (Shi et al., 2020; Simões et al., 2021). Cooling systems vary: evaporative cooling is efficient but consumes more water, while air cooling is less efficient but uses less water (Australia, 2022).

2.2. Recycled water as circular economy strategy.

The circular economy, in contrast to the linear 'take-make-dispose' model, minimizes resource inputs, waste, emissions, and energy loss through maintenance, reuse, remanufacturing, refurbishing, recycling, and long-term design (Geissdoerfer et al., 2017; Nikolaou & Tsagarakis, 2021). Wastewater treatment illustrates this by recovering water and safely disposing of it, crucial for public health (Salgot & Folch, 2018). Integrating circular economy principles into wastewater management can reduce industrial freshwater use by substituting it with recycled water, though this practice is rare in developing countries (Zyl & Jooste, 2022). Wastewater Treatment Plants (WWTP) vary by technology, effluent type, and water reuse requirements, with processes categorized as physicochemical, biochemical, and microbiological (Salgot & Folch, 2018). For green hydrogen production, tertiary treatments like reverse osmosis and ion exchange are essential for demineralization due to the high purity required for electrolyzer (Becker et al., 2023).

It is important to note that, regardless of the treatment level, sludge is always produced in WWTPs, necessitating effective sludge management (Yadav et al., 2021). While landfill disposal is common, alternative solutions exist with proper management. In China, approximately 30% of sludge is used in agriculture, adhering to the principles of the circular economy, while the rest is disposed of or incinerated (Wei et al., 2020). Additionally, WWTPs emit about 374 g of CO_2 per m^3 of treated effluent, primarily during secondary and tertiary treatment. Social acceptance of recycled water depends on its intended use and perceived risks. It is generally more accepted for low human contact applications, such as flushing and construction, but less so for high contact situations due to contamination fears. In water management, recycled water for industrial applications is preferable to linear economy methods like seawater desalination (Woods et al., 2022).

2.3. Seawater desalination as linear economy strategy

The most common seawater desalination method is reverse osmosis, which uses high-pressure pumps to force water through a semipermeable membrane, separating desalinated water from brine. The water recovery rate depends on the initial salinity and technology, averaging 42% (Jones et al., 2019). For producing high-purity water, additional processes beyond reverse osmosis are required to preserve electrolyzer lifespan (Becker et al., 2023). Key economic barriers to establishing a reverse osmosis seawater desalination plant include high CAPEX and significant electricity consumption (Darre & Toor, 2018), around 5 kWh/m^3 (Eke et al., 2020). Energy demands account for over 50% of OPEX, mainly due to the high power needed for pumping water through membranes (Judd, 2017).

Brine, the byproduct of desalination, contains high salinity, heavy metals, and various chemicals. Disposing of brine in the ocean, a linear economy strategy, can cause ecological impacts (Panagopoulos et al., 2019), such as increase local seawater salinity, reduce desalination plant efficiency and increase energy consumption (Missimer & Maliva, 2018). Dilution of brine mitigates marine biota impacts, but minor salinity changes can affect ecosystems (Darre & Toor, 2018). In regions like the Persian Gulf, with climates similar to Ceará, brine harms zoobenthos, echinoderms, marine algae, and coral reefs. Brine discharge and climate change could raise coastal temperatures by at least 3°C, affecting fisheries and communities (Le Quesne et al., 2021).

3. Methodology

This research employs the System Dynamics approach, combining qualitative and quantitative methods for exploratory and descriptive purposes (Cavicchi, 2016; Silberg et al., 2024). We analysed documents and conducted 11 interviews to identify key factors in Ceará's future GH hub, focusing on the water supply system (Sterman, 2000). Documents reviewed included State of Ceará Official Gazettes, government websites, and sites of companies with Memorandums of Understanding with the Ceará government. Gazettes were searched for "green hydrogen" from 01/01/2020 to 05/06/2023, yielding 20 relevant issues. These documents inform strategic decisions and partnerships for GH development.

Documents from various state water resource institutions were analysed, including the Strategic Management and Business Plan of the Water and Sewage Company of Ceará (PGECAGECE, 2023), and the Strategic Action Plan for Water Resources of Ceará (PAERHCE, 2018). These documents highlight recycled water as viable for industrial use. Law No. 16,033, which addresses non-potable water reuse in Ceará, was reviewed for legal aspects. Additionally, the EIA of Fortescue Future Industries and the GH Hub at CIPP were analysed to investigate technological decisions and socioecological aspects. This document analysis informed the modeling exercise and interview structure. Interviews aimed to explore specific water management issues related to the GH hub in Ceará, impacting socioecological and economic factors. A summary of the profile and objectives of each interview is shown in the table 1.

Table 1
Interviewee Profiles and Objectives for the study.

Interview	Profile	Date (dd/mm/year) and Duration (minutes)
E1	Coordinator in Energy Strategy of Ceará	04/11/2022; 39
E2	Hydrology Researcher	07/12/2022; 51
E3	Wastewater Treatment Researcher	10/05/2023; 50
E4	Industrial & Port Complex President	19/05/2023; 50
E5	Chemical Engineer, Water & Sewage Company	07/06/2023; 60
E6	Desalination and reuse Coordinator	14/07/2023; 40
E7	GH Engineering Specialist	24/07/2023; 56
E8	Marine Ecology Researcher	27/07/2023; 50
E9	Recycled water engineering coordinator	23/10/2023; 60
E10	Indigenous leader from surrounding communities	07/12/2023; 80
E11	Industrial Wastewater Treatment Manager	15/04/2024; 92

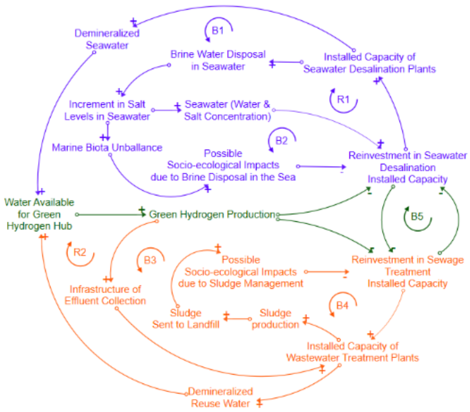
The System Dynamics approach involves five steps: (i) Problem Articulation, which identifies and defines issues that hinder system objectives; (ii) Dynamic Hypothesis Formulation, where assumptions about system behavior (e.g., exponential growth) are made, and Causal Loop Diagrams (CLD) are created to illustrate feedback loops; (iii) System Dynamics Model Formulation, which expands CLDs into stocks, flows, and variables, with clear boundaries to avoid extraneous issues; (iv) Testing and Validation, where model outcomes are compared with empirical data, and sensitivity tests are conducted; (v) Policy Development, which proposes scenarios based on simulations to identify leverage points that facilitate the system in achieving its objectives.

3.1. Causal Loop Diagram of GH's Water Supply

The Causal Loop Diagram was developed under two complementary perspectives, one considering a multifaceted interaction among technological, ecological, and social factors; and the other comparing circular and linear economy approach. Structurally, loops B1 and B3 are concerned to technological factor, encompassing variables related to installed capacity, GH production, and reinvestment. In addition, loops B2 and B4 involves social and ecological factors, encompassing variables related to waste from both technologies of water sources and its possible impacts. The loop R1 is related to ecological and technological factors, considering variables related to increment of salt concentrations in the seawater and the subsequent reinvestment in seawater desalination installed capacity. The loop R2 is related to socio-technological factors, encompassing the increment of effluent collection and the increment of installed capacity of recycled water. Figure 1 elucidates the system's variables and the identified feedback loops.

Figure 1

Causal Loop Diagram of water supply sources for GH hub.



The second perspective compares upper and lower parts of the CLD. It considers the linear economy approach, featuring balancing loops B1 and B2, along with reinforcing loop R1. Subsequently, it considers the circular economy approach, incorporating balancing loops B3 and B4, and reinforcing loop R2. Lastly, balancing loop B5 highlights the selection preferences for water supply sources.

Explaining with further details, in the linear economy approach, loop B1 commences as the installed capacity of the seawater desalination plant increases, raising the supply of demineralized water to the GH hub, enhancing GH production. This increase in GH production gradually diminishes the reinvestment in seawater desalination capacity over time, as the saturation of viable locations for new desalination plants or further expansion of seawater desalination installed capacity becomes a limiting factor due to increment of salinity levels in the sea. This strategy emerges from interviews E4, E6, E7, E9, and the EIAs conducted by both, Fortescue and CIPP. Loop R1 illustrates the direct impact of the increased seawater desalination capacity on brine water disposal into the sea, consequently elevating the salt concentration in seawater. This increase is likely to make the desalination process more costly due to both energy-intensive and detrimental to membrane longevity, requiring further reinvestment in desalination capacity. These insights were derived from interview E8 and E11.

Loop B2 considers the rise in seawater salt concentration potentially leading to a marine biota imbalance, with associated socio-ecological repercussions such as the prevalence of salt-resistant species and reduced fisheries activities. These effects may decrease the reinvestment levels in seawater desalination plants, informed by insights from interviews E2, E7, E8, and E10.

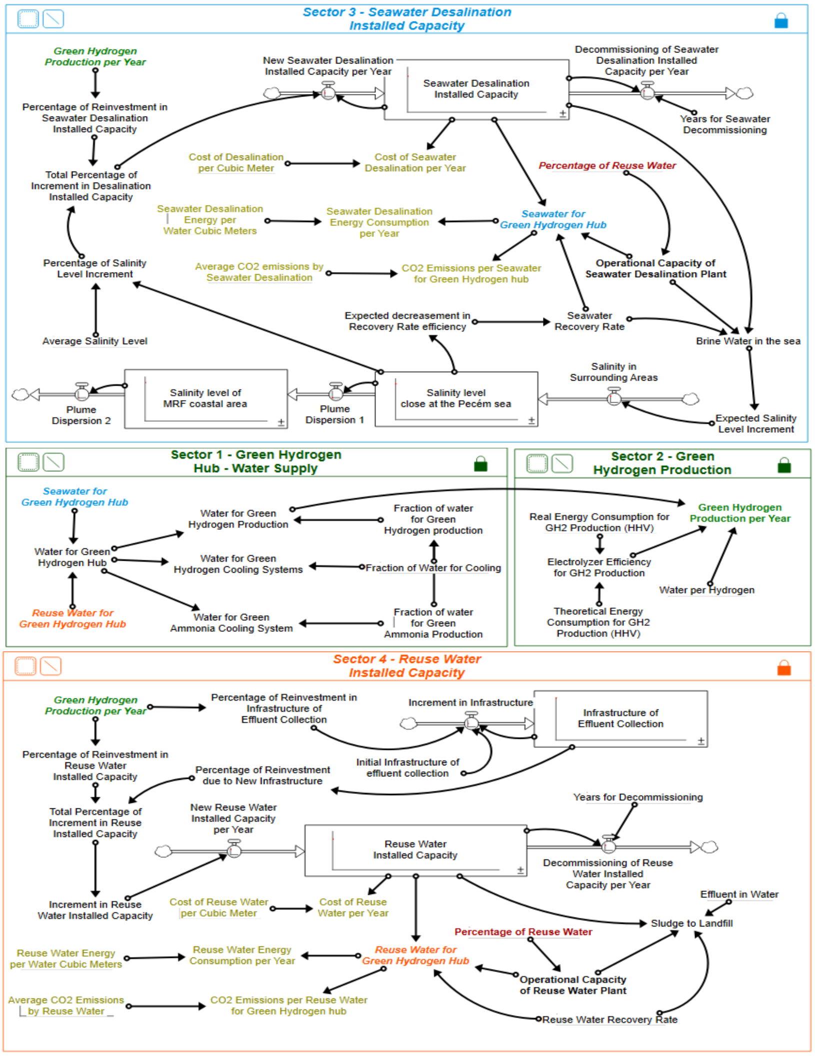
Conversely, the circular economy model initiates with Loop B3, showing the increment of the capacity of wastewater treatment plants. This loop influences the supply of demineralized recycled water, enhancing the GH production, causing a reduction in the reinvestment in recycled water installed capacity, due to a limited supply of sewage. Support for this loop comes from interviews E1, E2, E3, and E11. The loop R2 begins with the same logic as B3, however, the GH production leads to an increase in the infrastructure of effluent collection, which raises the installed capacity of recycled water. This strategy is legally supported by Law No. 16,033/2016 of the State of Ceará and corroborated by interviews E1, E2, E3, E4, E6, E9, and E11. Loop B4 begins with the positive impact of GH production on the infrastructure of effluent collection in RMF, which increases the capacity of wastewater treatment plants, thereby raising sludge production and its delivery to landfills. Increased landfill sites exacerbate sludge management challenges due to potential socio-ecological impacts, such as leachate leakage and greenhouse gas emissions. These side effects of the water reuse strategy were informed by interviews E3 and E6. Lastly but not least, the loop B5 drives the whole behaviour of the model by choosing the magnitude of circular versus linear economy approaches. This loop demonstrates that increased reinvestment in seawater desalination capacity leads to reduced reinvestment in sewage treatment capacity, and vice versa.

3.2. Stock and Flow Diagram of GH's Water Supply

The SFD objective is to estimate the GH production under different assumptions about water supply. The simulation period is adjusted to start in 2026, when the first hydrogen plant is supposed to start production and is adjusted to stop in 2050, when the production is expected to reach a threshold. The SFD is composed by four sectors. Sector 1 is called ***GH Hub***: first it aggregates the water supplies coming from sectors 3 and 4, and second it divides the water supply into three main uses (i.e., the GH plant cooling system, the GH production system, and the green ammonia cooling system). Sector 2 is ***GH Production***, where water coming from sector 1 is transformed into hydrogen. This sector takes into consideration both the efficiency of the process and the stoichiometric relationship between water and hydrogen. Sector 3 is for the ***Seawater Desalination Installed Capacity***, which is calculated by inserting initial values and adding a percentage of reinvestment from GH production, resulting in a growing brine water disposition at the sea over time, that creates plumes of salt water. Sector 4 is for the ***Recycled water Installed Capacity***, which is calculated by considering the water produced through tertiary effluent treatment, the percentage of recycled water in the system, the sludge production, and the increment in the infrastructure of effluent collection. The model is operated testing different percentages of reused water (in sector 3 and sector 4) that allow the exploration of different results for various socioecological aspects. The figure 2 shows the SFD developed and its main variables.

Figure 2

Stock Flow Diagram for the water supply of GH production.



The SFD can be analysed by starting on sector 1 looking at the variable "*Water for GH hub*" (WGHH) as shown in equation 1, which depends on two other variables that come from both sectors 3 and 4. These are the "*Seawater for GH Hub*" (SWGH) and the "*Reuse-water for GH Hub*" (RWGH). These major indicators can be calculated by the following equations:

$$WGHH = SWGH + RWGH \quad (01)$$

$$SWGH = SWIC \times OCSW \times SWRR \quad (02)$$

$$RWGH = RWIC \times OCRW \times RWRR \quad (03)$$

Where, for equation 2, SWIC is the "*Seawater desalination Installed Capacity*", OCSW is the "*Operational Capacity of Seawater Desalination Plant*", and the SWRR is the "*Seawater Recovery Rate*". For equation 03, the variable RWIC is the "*Recycled water Installed Capacity*", OCRW is the "*Operational Capacity of Recycled water Plant*", and RWRR is the "*Recycled water Recovery Rate*". The second equation that has a major impact on model behavior is about the operational capacity, that is driven by the chosen "*Percentage of Recycled water*" (PeRW). Both the "*Operational Capacity of Recycled water Plant*" (OCRW) and the "*Operational Capacity of Seawater Desalination Plant*" (OCSW) are represented by equations 04 e 05, basically, one is the remaining of the other:

$$\text{OCRW} = \text{PeRW} \quad (04)$$
$$\text{OCSW} = 1 - \text{PeRW} \quad (05)$$

The PeRW is the key variable of the system because it represents the choice made by decision makers about which approach will be preferred, the circular economy or the linear economy. Moreover, the PeRW has a major influence on the by-products of each water source, depicted by equation 06 for "*Brine Water Production Yearly*" (BWY), as well as equation 07 for "*Sludge Production to Landfill Yearly*" (SLY).

$$\text{BWY} = \text{SWIC} \times \text{OCSW} \times (1 - \text{SWRR}) \times \frac{Seconds}{Year} \quad (06)$$
$$\text{SLY} = \text{RWIC} \times \text{OCRW} \times (1 - \text{RWRR}) \times \frac{Seconds}{Year} \quad (07)$$

In the sector 01, the water for GH hub is applied in three uses represented by the equations 06, 07, 08, and 09. Where, in the equation 08, WGHC is "*Water for GH Cooling*" and FWC is "*Fraction of Water for Cooling System*". The WGAC, in the equation 09 is the "*Water for Green Ammonia Cooling System*, and FWAC is the "*Fraction of Water for Ammonia Cooling*". The WGHP, in the equation 10 is the "*Water for GH Production*" and the FWGP is the "*Fraction of Water for GH Production*".

$$\text{WGHC} = \text{WGHH} \times FWC \quad (08)$$
$$\text{WGAC} = \text{WGHH} \times FWAC \quad (09)$$
$$\text{WGHP} = \text{WGHH} \times FWGP \quad (10)$$
$$FWGP = 1 - FWC - FWAC \quad (11)$$

In the sector 2, the hydrogen production is calculated by the "*Electrolyzer Efficiency for GH Production*" (EEGH) and the stoichiometric relationship between water and hydrogen which forms the calculation of "*GH Production Yearly*" (GHPY), represented by the equations 12 e 13, respectively.

$$EEGH = \frac{TEC}{REC} \quad (12)$$
$$GHPY = \frac{(WGHP \times Water\ density)}{Water\ per\ green\ hydrogen} \times EEGH \times \frac{Seconds}{Year} \quad (13)$$

Where, in the equation 12, the variable TEC is the "*Theoretical Energy Consumption for GH Production - High heating value*", and REC is the "*Real Energy Consumption for GH Production - High heating value*". Also, in equation 13 the variable WGHP is the "*Water for GH Production*". Variables for the SFD were collected in multiple sources, the table 2 shows the values from the scenarios analyses and ranges, if applicable, for the uncertainty test, and references for the variables that have been presented so far.

Table 2

Values of the variables.

Variable	Equations	Value	Unit	Reference
SWIC	01	0,32	m^3/second	Fortescue (2023)
SWRR	01	0,4	Dimensionless	Panagopoulos et al. (2019)
RWIC	02	0.032/0.32	m^3/second	Complexo do Pecém (2023)
RWRR	02	0,95	Dimensionless	E3
PeRW	04; 05	Scenarios	Dimensionless	E3, E4, E6, E7, E8, E9, E11
FWCS	08; 11	0,8	Dimensionless	Fortescue (2023), E7
FWAC	09; 11	0,03	Dimensionless	MacFarlane et al. (2020)
TEC	12	39,4	kWh/ Kilograms of green hydrogen	Jang et al. (2022)

REC	12	54	kWh/ Kilograms of green hydrogen	Lee et al. (2022)

For the development of policies, four scenarios based on the percentage participation of recycled water in the system, represented by the variable *PeRW*, were proposed. Scenario 1, grounded in the EIA for the GH hub at CIPP, proposes that the PeRW variable is 10%. Scenario 2 suggests that the PeRW variable will be 0%, meaning only seawater desalination will be utilized, based on the EIA for the GH plant by Fortescue and interviews E5, E7, E8, E9, and E11. Scenario 3 proposes that the PeRW variable will start at 0% and raise until 50%, based on PAERHCE, PGECAGECE, and interviews E1, E3, E4, E7, E9, and E11. Scenario 4 proposes that the PeRW will 100%, meaning only recycled water will be used to supply the GH hub.

4. Results

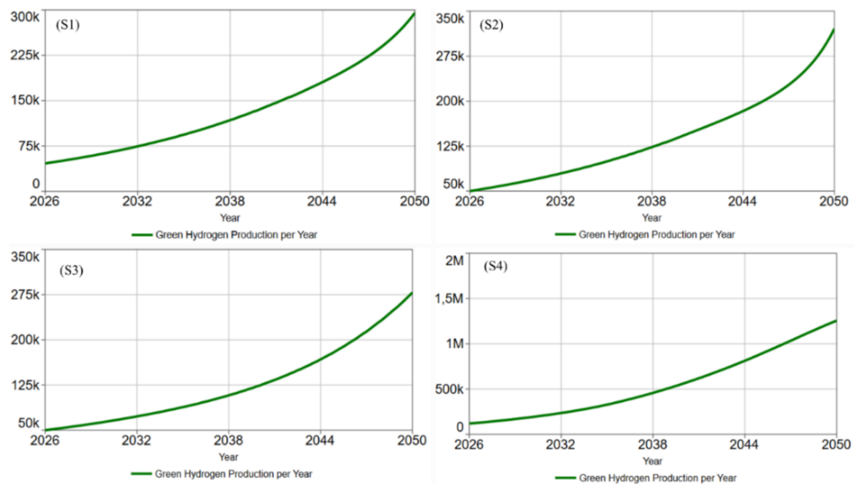
The following section compare the variables behavior in 4 different scenarios over 2026 to 2050 comparing the utilization of water sources under circular and linear economy frameworks, represented by the recycled water and seawater desalination, respectively.

4.1. GH production across water sources

The values of GH production changes significantly across the developed scenarios, while the pattern behavior remains the same, as shown in the figure 3. Scenario S1, represented by 10% of the water used being recycled water (PeRW = 10%), the GHPY begins at approximately 46,200 tonnes in 2026 and steadily increases to about 295,000 tonnes by 2050, following an exponential growth trend. This scenario suggests a significant but gradual increasement in GH production over the years. Scenario S2 represents a condition where no water is recycled water (PeRW = 0%), relying solely on seawater desalination. The production starts at around 50 kilotons in 2026 and escalates to 321 kilotons by 2050. The exponential growth observed here is similar to Scenario 1 but at a higher initial and final production volume, indicating a substantial increase in GH production when using desalinated seawater.

Figure 3

Green hydrogen production per scenario

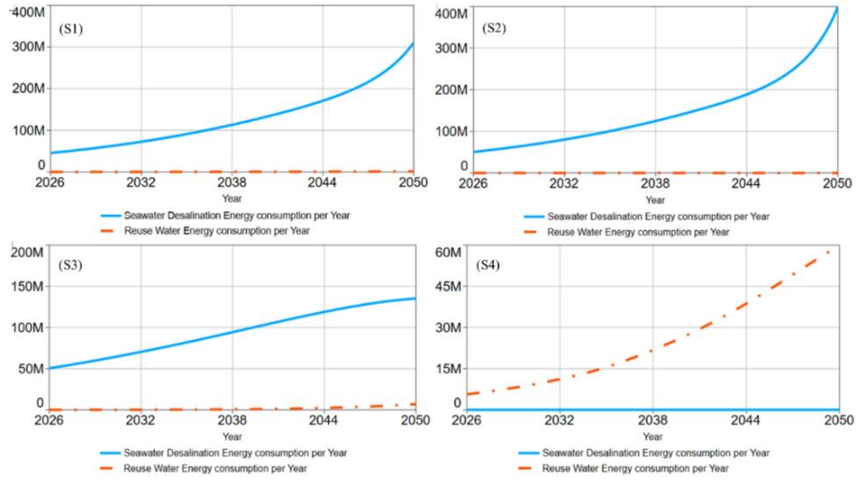


In Scenario S3, the percentage of reused water increases linearly from 0% to 50% over the years. The initial production begins in 50,000 tonnes in 2026, rising to around 279,000 tonnes by 2050. The growth trend in this scenario is balanced, reflecting the gradual increase in recycled water over time, with no substantial increment in GH production. Scenario S4 assumes that all water used is recycled water (PeRW = 100%). The production starts at approximately 119 kilotons in 2026 and reaches up to 1,26 million tonnes by 2050. The exponential trend in this scenario is significantly steeper compared to the other scenarios, demonstrating the highest initial and final production volumes due to the complete reliance on recycled water. Comparing these scenarios, Scenario 4 shows that in 2026 the GHPY is 140% to 150% higher than the other ones. These results can be explained by the recovery rate of recycled water being 95%, while the initial recovery rate for seawater desalination is 40%, which can decrease as the salinity of seawater increases. The same scenarios show that in 2050, the GHPY is, in average, 320% higher than the other ones. Additionally, the difference between Scenarios 1, 2, and 3 is relatively small, indicating that partial and progressively increasing in recycled water leads to similar production levels. Most notably, once GH production plants are operational, the increment of recycled water cannot significantly boost GH production. Therefore, selecting the appropriate water source at the beginning is essential for optimizing production capacity in the long term.

The energy consumption for seawater desalination and recycled water varied significantly across the four scenarios, reflecting the different technological, as illustrated in Figure 4. In Scenario 1, the energy consumption for seawater desalination increases from approximately 45.4 to about 310 million kWh yearly by 2050, with recycled water representing minimal energy consumption, varying from 56k to 1.35 million kWh yearly by 2050. In Scenario 2, the energy consumption for desalination rises sharply from 50 to 400 million kWh by 2050, highlighting the high energy demand of desalination alone. Scenario 3 shows desalination energy use growing from 50 million kWh to 135 million kWh, while energy consumption for recycled water rises from 0 to about 6.9 million kWh, reflecting a more balanced energy profile as recycled water usage increase. Among S1, S2, and S3, the last one is the most balanced in terms of GH production and energy consumption. In Scenario 4, the energy consumption for recycled water starts at around 5.66 and rises to approximately 60 million kWh by 2050, presenting the best cost-benefit ratio, with very high levels of GHYP and lower overall energy consumption. This scenario underscores the efficiency of utilizing recycled water for large-scale hydrogen production.

Figure 4

Energy consumption per scenario.



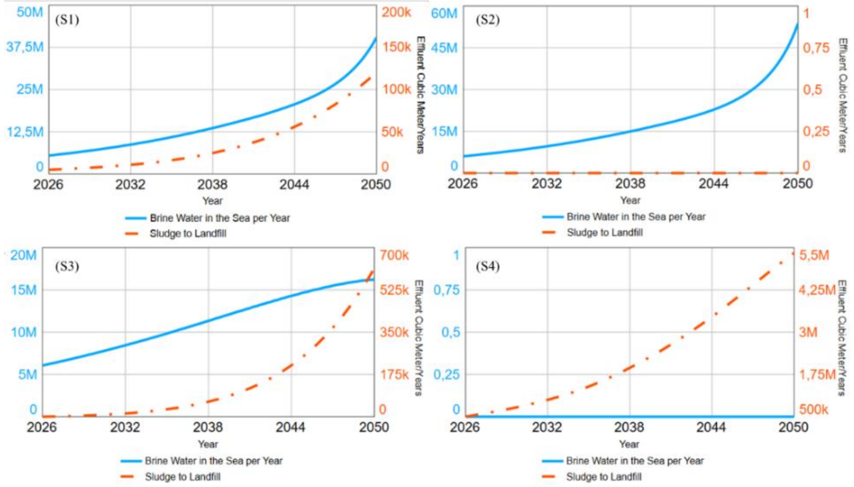
Regarding to operational aspects of the GH hub simulated across 25 years, S4 shows the best performance due to highest values of GH production and the lowest values of energy consumption. The S2 is the second in values of GH production, however, is the one with the highest energy consumption.

4.2. GH impacts due to water source choices.

Both brine water and sludge production changes significantly across the developed scenarios, meanwhile the behavior pattern remains the same in most scenarios, as shown in the figure 5. In Scenario S1, brine water production starts at approximately 5,5 million cubic meters and rises to about 40 million cubic meters, while sludge production increases from 5 kilo effluent cubic meters to about 120 kilo effluent cubic meters. Scenario S2 shows brine water production starting at around 6 and rising to nearly 54 million cubic meters in 2050. In Scenario S3, brine water production starts at approximately 6 and increases to around 16.2 million cubic meters, with sludge production rising from zero to about 616 kilo cubic meters at the end of the simulated period. Scenario S4 indicates production of sludge starting at approximately 505 kilo effluent cubic meters and rising to about 5.5 million cubic meters by 2050.

Figure 5

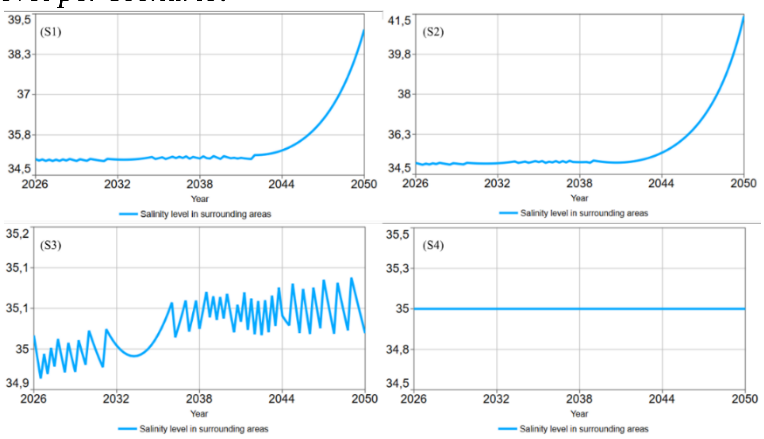
Brine water and sludge production per scenario.



The stock of salinity level close at the Pecém sea, shown in figure 6, varies across the four scenarios, reflecting different water management strategies. In Scenario 1, the salinity level starts at 35 kg/m³ and rises to around 39 kg/m³ by 2050, indicating that partial recycled water assists to mitigate drastic salinity changes, however, by 2044, the stock of salinity level starts to present an exponential growth trend.

Figure 6

Stock of salinity level per scenario.



Scenario 2, with no recycled water, shows a salinity increase from 35 kg/m³ to nearly 41.4 kg/m³, highlighting the higher brine accumulation from desalination and the stock of salinity level starting to present an exponential growth trend higher than S1. Scenario 3 starts at 35 kg/m³ and slightly increases to 35.1 kg/m³ by 2050, showing a controlled rise due to increasing recycled water. Scenario 4 keeps the salinity unchanged at 35 kg/m³, as no brine water is discharged. Comparing the scenarios, Scenario 3 is the most balanced in managing salinity impact while integrating recycled water, whereas Scenario 2 has the highest increase in salinity levels. Scenario 4 offers the best outcome with no impact on salinity levels, highlighting the benefits of a circular economy approach. Considering the GH impacts due to water source choices, S4 shows the best performance, demonstrating the benefits of circular economy. Relying solely on seawater desalination worst performance in all the variables simulated. One of the most concerning's results from S2 is the higher value of salinity in the surrounding areas of the hub. Still regarding to the salinity level, the scenario S3 shows a disturbance, however, the system manages to stabilise itself.

5. Discussion

The evaluation of water supply sources for GH production at the CIPP highlights crucial aspects of the social-ecological-technological system (SETS), particularly its resilience and path dependencies. These concepts are especially relevant for urban areas like MFR, which encompass formal and informal settlements and face environmental impacts from urban supply chains and emissions. Relying on desalination may create path dependencies, where stressors (e.g., increased sea salinity) and shocks (e.g., fish mortality, community riots) can lead to undesirable outcomes (e.g., resource-intensive or socially unjust regimes) (Krueger et al., 2022). To avoid unsustainable practices and build resilience with the GH hub projects, our model suggests using at least 50% recycled water from the project's inception. The technological component of the SETS is crucial for GH production. Our model indicates that choice about the water sourcing significantly affect operational scale and environmental impact due to the low water recovery rate of seawater desalination and its high energy demands. Social factors within the SETS also influence these technological choices. The Ceará government has not taken effective steps to support recycled water systems, leading companies to favour seawater desalination as a safer option. This decision exposes a governance gap, prioritizing corporate needs over environmental conservation and the welfare of traditional communities.

Our model suggests that relying solely on recycled water could increase effluent collection to 4.3 m³/second, creating a positive feedback loop between hydrogen production and recycled water demand, as shown in both the CLD and SFD. This finding aligns with Navarro (2018) in Spain, who noted the advantages of recycled water over seawater desalination, and with Woods et al. (2022) in Australia, who found recycled water to be more viable for GH production. Comparing water supply options for a GH hub between Portugal, as described by Simões et al. (2021), and the CIPP in Ceará reveals significant differences. The authors found that in some Portuguese regions, public grid water is the best option due to lower costs and higher quality for industrial use. However, in regions where grid water is scarce and contains dissolved salts, recycled and surface water become viable alternatives near urban and rural areas, respectively. They also concluded that seawater desalination is the least suitable option due to legislative and techno-economic issues (Simões et al., 2021). In contrast, Ceará cannot rely on public grid water for the GH hub at CIPP due to frequent water shortages in its semi-arid region. While seawater desalination faces fewer legislative challenges in Ceará, making it a preferable option according to several EIAs, recycled water has been considered for industrial use since 2011. However, no effective measures have been taken to implement this solution.

Several factors hinder the implementation of resource recovery in WWTPs, such as recycled water and sludge utilization. In São Paulo, Brazil, the main barriers are: (1) insufficient planning during plant design for resource recovery, (2) outdated legislation that does not allow sludge reuse, and (3) low demand for recycled water near the plants (Chrispim et al., 2020). Our interviews revealed similar barriers in Ceará, with an additional challenge related to water pricing. In Ceará, the industrial sector buys reservoir water at 3.27 Brazilian Reais per cubic meter (CONERH Decision No 01/2022 of 28 January 2022 Provides for Charging for the Use of Surface and Underground Water Resources in the Domain of the State of Ceará or the Union, by Delegation of Competence., 2022), while the projected cost for recycled water ranges from 6.00 to 8.00 Brazilian Reais per cubic meter. This financial disparity significantly hinders its adoption at the CIPP.

The potential ecological impacts within the SETS framework highlight the significant negative effects of seawater desalination. Ceará could experience marine life disruptions similar to those on the Egyptian Red Sea coast and in Cyprus, where brine discharge has caused changes and high mortality in marine species like the macrobenthic community and Posidonia oceanica (Nasr et al., 2019; Xevgenos et al., 2021). This could threaten traditional communities dependent on fishing and tourism. Artisanal fishing, essential for many families in Ceará, competes with shrimp farming and is economically viable (Marques et al., 2021; Queiroz et al., 2020). Without artisanal fishing, reliance on shrimp farming could increase, further endangering marine life. The lack of a social monitoring system impedes policy improvements to equitably distribute benefits and mitigate harms to traditional communities. Addressing these issues requires holistic system dynamics models that integrate water sources, technological preferences, community protection, and environmental conservation.

Therefore, the CLD and SFD indicate that adopting a linear economy approach in large-scale, export-oriented GH production can exacerbate social inequalities and increase environmental degradation (e.g., shrimp farming), already at risk due to increased salinity. In line with (Almaraz et al., 2024), we argue that abundant solar and wind energy, coupled with a well-established industrial and harborside infrastructure, cannot be decisive arguments for the hydrogen economy. Therefore, it is imperative to consider the influence of hydrogen production on social and ecological aspects along the GH value chain. Moreover, the global hydrogen transition, driven by the energy demands of developed countries and optimistic GH narratives, risks perpetuating neo-colonial exploitation (Kalt & Tunn, 2022). To avoid these adverse impacts, we recommend stakeholders adopt a circular economy approach, guided by the CLD and SFD results, to better address SETS and ensure energy justice for the GH project in Ceará.

6. Conclusion

This study uses a novel mixed-methods approach based on system dynamics to analyze SETS dynamics in Ceará's water supply for GH production at CIPP. We explore the feedback effects of circular versus linear economy approaches on social and ecological factors over 2026–2050. Through literature review, stakeholder interviews, document analysis, CLD and SFD development, and SFD calibration, we compare the impacts of seawater desalination versus recycled water on GH production. Key variables include green hydrogen production, energy consumption, waste production, and stock of salinity. Our study contributes to the literature by offering a pathway to analyze cross-scale governance of SETS in the context of the energy transition (Krueger et al., 2022). The SETS framework reveals that policy interventions focusing solely on hydrogen production via a linear economy approach led to unsustainable production and energy injustice. Sustainable production results from collaboration among stakeholders and communities, a core principle of the circular economy (Geissdoerfer et al., 2017). While the circular economy promotes energy justice, it alone cannot prevent potential adverse effects on traditional communities (Müller et al., 2022). System dynamics proved effective for comparing sustainable and unsustainable practices within a SETS (Cavicchi, 2016; Silberg et al., 2024).

We determined that recycled water is the most viable water source for GH production due to its higher output, capacity to promote social development, preservation of marine life, and protection of traditional communities compared to seawater desalination. It also fosters stakeholder collaboration to overcome barriers for GH production, such as community acceptance and water scarcity, positioning Brazil as a global leader in the GH sector (Garlet et al., 2024). More structured data on social and environmental aspects would further support decision-making.

7. References

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