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Life Cycle Assessment of Reverse Osmosis Desalination: Environmental Impacts and Sustainability Improvements through Renewable Energy integration and Brine Valorization

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À la mémoire de mon père, pour tout ce que je fais encore en pensant à lui.

À ma mère, dont l'amour et la tendresse ont a été mon abri et mon moteur.

- *Boutheina*

To my mother, for giving me a sense of purpose, listening to my endless rents and turning every school drop- off into a daily act of love and patience

To my dad, for always believing in me and making me believe in my self

To Chanez,for the quiet comfort of your presence, the genuine care you gave so naturally, a sister at heart

To Bouchera my dearest of friends, for standing by my side ever since high school through every high and low

With all my love,

Selma

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List of abbreviations

AB Activity Browser. 10

BAU Buisness As Usual. 1, 12, 18

BRV Brine valorization. 2

ED Electrodialysis. 9

EDR Electrodialysis Reversal. 9

ERD Energy Recovery Devices. 6

FO Forward Osmosis. 9

LCA Life Cycle Assessment. 1, 9, 12

MD Membrane Distillation. 9

MED Multi-Effect Distillation. 9

MSF Multi-Stage Flash. 9

NF Nanofiltration. 9

RE Renewable Energy. 2, 12

RO Reverse Osmosis. 1, 4, 6, 9

SWD Seawater Desalination. 1

VC Vapor Compression. 9

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Introduction

Development comes with various constraints, and among the most pressing of the 21st century is the availability of conventional freshwater, driven by climate change and demographic growth. In arid and semi-arid regions such as north Africa, the water crisis is imminent as projections show rainfall is expected to drop significantly by 2050. To cushion the impact and decrease regional vulnerability, **desalination** has emerged as a non-conventional alternative.

Reverse Osmosis (RO) is the world's lead desalination technology, it surpasses its contestant demineralization technologies [1] being the most energy efficient process. This dissertation is a case study of the **UTE Desaladora** plant located in Skikda, Algeria, producing **100 000 cubic meters** a day through the RO process.

Seawater Desalination (SWD) appears to be a necessity given the urgency of the matter, but also a challenge, the interdependency between water and energy, often referred to as **water-energy nexus** is the central concern of this work.

In this context, we have conducted a comprehensive, multi-scenario **craddle-to-gate** Life Cycle Assessment (LCA) with a focus on three main impacts :

- Climate change : Global Warming Potential
- Marine eco-toxicity
- Fossil Fuel depletion

An LCA approach allows for multi-criteria evaluation ; energy demand, chemical dosage and brine discharge are key environmental concerns in desalination. Consequently, the objective of this study is to assess the environmental performance of RO desalination through projections of various improvements.

For that end, several scenarios have been modeled using the **Activity Browser** interface and the **ecoinvent 3.11** database. As a first step, scenario 1 represents the base case to which all other projections will be compared to ; the Buisness As Usual (BAU).

Then, in alignment with the national ambition of incorporating up to 27% of Renewable Energy (RE) within the conventional energy mix stipulated in the **Program for the Development of Renewable Energy and Energy Efficiency**, three scenarios have been modeled, incrementing gradually the RE percentage :

- Scenario 2 : 10% RE
- Scenario 3 : 20% RE
- Scenario 4 : 30% RE

with the main renewable being **solar energy (75%)** and **wind energy (25%).**

The fifth scenario presents a feasibility and scalability study of a potential system expansion within the ***Dual Material and Energy Valorization of Reverse Osmosis Brine : A Modular Engineering Solution Adapted to the UTE Desaladora Skikda Plant*** research project.
The expansion consists of Brine valorization (BRV) , the electrolysis of brine produces **hydrogen gas**, **sodium hypochlorite** and **sodium hydroxide**, all three will be re-injected in the desalination process in a circular economy approach, coupled with a fuel cell – electrolyzer loop aiming to improve energy efficiency.
The results show a significant decrease in carbon footprint, and consequently, climate change, that accompanies the RE integration, confirming our hypothesis.
On the other hand, the fifth scenario showed interesting results that deviated from initial expectations, the BRV benefits certain impacts but there are significant environmental trade-offs ; the electrolysis is energy extensive compared to the regular base case consumption, although there is a partial energy recovery through the fuel cell.

This study seeks to adduce environmental insights, revealing environmental trade-offs and showing how different energy configuration can influence the environmental footprint of SWD.

Chapter 1

Internship Description, Motivation and Problematic

1.1 Presentation of the Host Company

The SWD plant **UTE Desaladora** located in the eastern side of Skikda's petrochemical zone, in an area called *Diar Chitan*, started operations in **September 2009**, providing the petrochemical refinery as well as the city of skikda and its nearby provinces (approx. 70 000 people) with potable water, thus enhancing the water supply of the region, that has long suffered from water shortages.
The plant's daily production goes up to $100000 m^3$, it was constructed by the Spanish

Figure 1.1: UTE Desaladora location

group **GEIDA** ; a consortium of four entities : **Cobra, Sadyte, Befesa** and **Codes**,

the group owns 51% of the shares, with the remaining 49% belonging to AEC.
The company has 60 employees, 25 of whom are employed by the parent company while the remaining staff are subcontractors. The unit retail price is $0.70 USD/m^3$ and two major clients are :

- SONATRACH (20%)
- l'Algérienne des eaux (ADE) (80%)

The facility is supplied with electricity from **SONELGAZ** through two high voltage lines. The primary one powers the station under normal conditions while the secondary ensures backup. At full capacity, the station consumes $3.56 KWh/m^3$ [2].
The installation operates using a RO process, it's equipped with 5 membrane modules performing in parallel, with the production capacity of $20000m^3$ each.

1.2 Process Description

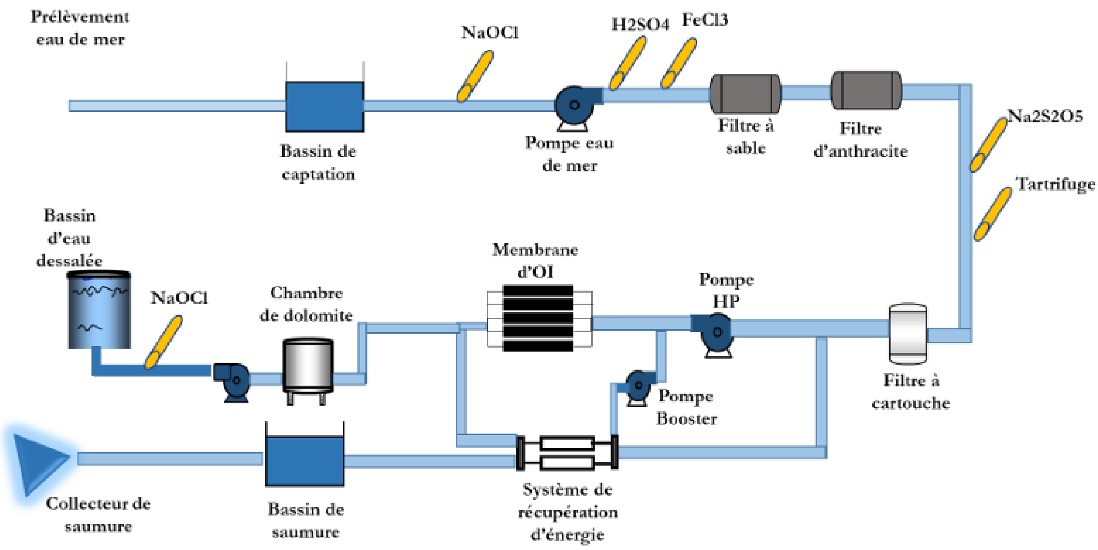


Figure 1.2: Overview of the Desalination Plant

1.2.1 Water Intake

The water is supplied from the Mediterranean through an open water intake system, meaning the water is captured to the pipeline by gravity at the flow rate of $1m/s$. The extends $1km$ offshore in a south-north direction reaching a depth of 100 m
The intake system has a shorter and more superficial canal. Its equipped with a strainer

designed to eliminate large impurities, the two rotating screens provide additional filtration aimed at capturing materials larger than 1 mm such as shellfish, algae and other crustaceans that might be present in raw seawater.
After passing through the rotary screens, the water flows into **sump reservoirs** where significant amount of water is pumped to pretreatment through **6 seawater pumps** with the capacity of $1800m^3/h$ each.

1.2.2 Pre-treatement

In the single shaft collector and before pretreatment, **scale inhibitor** is injected to **prevent fouling** as minerals present in seawater can precipitate and form scale deposits. After that, the water goes through a **two stage filtration** at horizontal pressure at the respective speed rates of 8.8 and $14.5m/h$. Pretreatment is crucial as it protects the equipment, notably the RO membranes, from damage and enhances water quality by eliminating particles that may interfere with the main filtration.

The installation includes **25 sand filters**with the capacity of $135m^3$ **each**, these filters are designed with a top-bottom flow, passing through an under-drain system composed of 220 nozzles, and multiple filtering layers that consist of two layers of coarse industrial sand, with the lower layer being coarser than the upper one ($2-4mm$ and $1-2mm$respectively). These pressure sand filters can eliminate impurities with diameters down to 40 µm.
The second stage anthracite filters have the same characteristics, the main distinction lies in the diameter of the anthracite coal and the sand. The water exiting the two stage filtration shows a significantly reduced level of suspended solids as well as other undesirable components such as oils, odors and heavy metals.

1.2.3 Micro-filtration

The final phase preceding RO is **micro-filtration** or depth filtration, it is crucial for membrane protection as its particle size exclusion reaches as little as 5 µm. The water undergoes **cartridge filters**, the cartridges are grouped in **10 high pressure housings** containing **280 units** that measure 2 inches in diameter and 60 inches in length.

1.2.4 Reverse Osmosis

Reverse osmosis is the opposite phenomenon to natural osmosis ; it forces water to flow from a higher concentration to a lower concentration by applying high pressure. This is achieved through extremely energy-intensive **high pressure centrifugal pumps**, their motor drive is $2MW$ at $6kV$ with the **flow rate of** $863m^3/h$ at $70bar$.

The installation has 5 RE skids that each have the nominal capacity of 20 000 m^3/j ; the RE membranes, being the key component in the system, are grouped in pressure vessels containing 7 spiral wound membranes, this configuration is the most extensively used as it aims to boost the surface area ($400ft^2$) in a compact volume.

An RO membrane is a semi-permeable barrier that allows clean water (permeate) to pass through while filtering any undesirable substances, it is made of thin-film composite (TFC) that combines : a dense active layer, a micro porous intermediate layer and a backing layer. The model used is the **hydranautics SCW5-LD** (sea water composite 5th gen, low differential pressure), it's nominal filtration is **47% permeate** and **53% concentrate**.

The plant is equipped with an energy recovery system based on the principle of positive displacement and isobaric chambers. **The pressure exchangers** (PX),play a huge role in minimizing energy consumption, recovering energy from the high pressure brine reject stream onto incoming seawater. These Energy Recovery Devices (ERD) are coupled with booster pumps that ensure the feed-water maintains a consistent pressure through the skids.

Table 1.1: Membrane Characteristics for SCW5-LD

Characteristic	**Value**
Membrane Model	SCW5-LD
Membrane Type	Thin Film Composite (TFC)
Permeate Flow Rate	34.1 m^3/day
Active Membrane Area	400 ft^2
Recovery Rate	47%
Concentrate Flow Rate	53%
Operating Pressure	60-70 bar
Operating Temperature	45°C (max)
Salt Rejection Rate	99%
Max Operating Pressure	800 psi
Membrane Material	Polyamide Composite

1.2.5 Post-treatment

The post treatment sub-process consists of adapting the permeate to the client's requirements. At the outset, right after the RO process, the water is directed to **10 calcite chambers** where **Calcium Carbonate $CaCO_3$** is dissolved, this mineralize the water and increases its hardness and consequently, stability. Following that, **Carbon Dioxide CO_2**is injected in the water to enhance the minerals adhesion as well as regulate the pH levels, preventing corrosion of pipes and other equipment.

Lastly, **Sodium hypochlorite NaOCl** is integrated for disinfection purposes, thus preventing biological microorganisms and pathogens from growing,it is an anti-microbial agent.

Chapter 2

State of the Art and Bibliographic Research

2.1 Introduction to Desalination

Water scarcity stands as an undeniable global crisis, recent data reveals a growing gap between the supply and demand of fresh water, it's roughly estimated that freshwater use now surpasses sustainable supply by 40%, with projections of 55% by 2030 [3]. This imbalance is mainly driven by population growth, pollution, and water-intensive economic developments [4].
Desalination which in literal terms means "salt removal", is one of humanity's most ancient water-treatment methods [4], though it didn't become economically viable on an industrial scale until the 1950s [5]. Up to date studies assessed 15,906 desalination plant as operational all around the world, with an estimated production capacity of 95.37 million m^3/day (34.81 billion m^3 per year) [6]. Despite relying on multi-step physical chemical and energy-driven separations to produce potable water, desalination remains energy-intensive since most plants still depend on fossil fuels for power , brine disposal is also a major environmental problem to tackle [7], additionally, it is often inaccessible due to energy or funding gaps in regions of blockades and damaged infrastructure in conflict zone. This leaves millions reliant on unsafe or insufficient water supplies [8].

2.2 Desalination Technologies

Desalination techniques are broadly divided into two main categories : thermal and membrane based technologies. Thermal-based desalination technologies rely on a simple principle and copy the natural water cycle by applying heat to seawater to evaporate freshwater vapour, which is then condensed into potable water. The three most common thermal

processes are : Multi-Stage Flash (MSF),Multi-Effect Distillation (MED),andVapor Compression (VC) [4]. Membrane based technologies are more industrially mature and notorious in regions like the Middle-East due to their economic and low carbon operation [4]. They can be classified into three main categories: pressure-driven membranes, including Reverse Osmosis (RO) and Nanofiltration (NF), electrically driven membranes, such as Electrodialysis (ED) and Electrodialysis Reversal (EDR), and thermal- and osmosis-driven membranes, encompassing Membrane Distillation (MD) and Forward Osmosis (FO) [4]. These groups represent the primary separation mechanisms used in modern desalination processes.
Particular attention is given to **reverse osmosis**, which currently represents the gold standard in membrane-based desalination due to its maturity, efficiency, and low energy consumption.

2.3 Life Cycle Assessment

There is growing concern about the environmental sustainability of desalination, mainly due to its negative impacts on both marine ecosystems (from brine disposal) and the wider environment (because of its heavy reliance on fossil-fuel-based energy). These issues make Life Cycle Assessment (LCA) especially relevant ; it is the ISO-standardized (14040/14044) method used to evaluate environmental impacts from “cradle to grave” [9]. LCA is a practical and widely used tool in the environmental field to assess how systems or products perform ecologically [14]. In this study, it’s applied to the full desalination process : energy and chemical use membrane production, and waste management. Conducting this analysis requires following the four key phases of the standardizedLCA framework :

1. Goal/Scope Definition establishes the functional unit (typically 1 m^3 of product water) and system boundaries.

2. Life Cycle Inventory quantifies resource inputs and emissions.

3. Impact Assessment evaluates consequences across categories like climate change and eco-toxicity.

4. Interpretation identifies improvement opportunities [9].

Life cycle assessments are usually conducted using specialized software (commercial and/or open-source) for an easier and fluid impact interpretation ;in desalination related LCA the mainstream popular choices are : SimaPro GaBi and Umberto , openLCA is an open source alternatives made by GreenDelta it prioritize transparency and customisation and is best suitable for educational purposes [10]. Activity Browser (AB) is another open source tool but more of a research focused software as it is primarily used in academic contexts ; it is based on the Brightway2 framework developed in python , this feature makes it highly personalized but rather technically niche [11]. This tool allows for fast LCA calculations across multiple scenarios, reference flows and impact categories, together with advanced techniques such as [12],[15] :

- Scenario or parametric LCA.
- Graph explorer.
- Uncertainty modeling.
- Advanced analyses : Monte Carlo, Global Sensitivity Analysis, etc.

An environmental study's primary aim is not to gather information but ultimately to communicate results that are feasible, accurate, comprehensible, inspiring and robust [12]. For this purpose, two different types of LCAs have emerged : **attributional** and **consequential LCA**

- **Attributional LCA** quantifies the actual environmental flows to and from the life cycle of a product or system as it operates, without considering broader system changes [14].
- **Consequential LCA** estimates how environmental flows would change as a result of potential decisions or changes in the system [14].

Similarly, characterization modeling, meaning the choice of indicators, distinguishes between two approaches : **midpoint**and **endpoint**.

- Midpoint : traditional characterization chooses a midpoint earlier in the cause-effect chain [14].
- Endpoint indicators align with the purpose of LCA, directly representing damage to areas of protection [14].

The **ecoinvent v3.11** data base, is an up-to-date version launched in 2023 with a chosing feature between consequential and attributional LCA .The ecoinvent Association was created by the Swiss research institutions ETH, EPFL, Empa, Agroscope and the Paul Scherrer Institute [16]. It was chosen for it's santardized, transparent, consistent, globally trusted environmental data associated with variant activities.

Key findings of the comparative analysis of different desalination plants technologies show that the RO method surpasses both MSF and MED in terms of efficiency and carbon dioxide emissions. A recent Persian Gulf study done on an RO desalination plant exhibits its competitive greenhouse gas emissions: 3.44 kg CO_2 equivalent per m^3 of potable water [17]. Similarly, in regard to energy consumption top performing RO plants use as little as little as 2.5–2.8 kWh/m$^{\mathbf{3}}$[13] whereas MSF and MED require much more :about 13.5–25.5 and 6.5–11 kWh/m$^{\mathbf{3}}$ respectively.[13]
These result vary slightly depending on energy source. Increasingly, desalination plants are gravitating toward a hybrid approach by implementing renewable energy sources such as Solar PV and wind power.[13]

Chapter 3

Methodology

3.1 Aims and Scope

This study aims to conduct a Life Cycle Assessment (LCA) of the Reverse Osmosis desalination to evaluate the sustainability performance and assess the environmental impact associated with this process along with supporting Algeria's ambition of integrating **30% of Renewable Energy (RE) sources** to the current energy mix, **five comparative scenarios**will be studied ; Buisness As Usual (BAU), then incrementally increasing the renewable's share by 10%, 20% and 30%,the fifth scenario proposes a system expansion through brine valorization, exploring a circular approach.

This work is based on the **UTE Desaladora Skikda desalination plant** and is structured around the following objectives :

- To assess environmental impacts related to the current operational practices ,establishing a baseline scenario for comparison.
- To evaluate gradual RE implementation (10%, 20%, 30%) in alignement with the national renewable energy program, aiming to reach **27% of RE sources** by 2030, with the reference point being the BAU scenario.
- To model and assess a brine valorization system expansion, enabling the recovery of several byproducts including hydrogen gas, hypochlorite and sodium hydroxide, proposing a sustainable, circular approach system optimization.
- To benchmark Algeria's performance against global best practices.

This study follows the **ISO 14040** and **ISO 14044** standards that define the internationally recognized framework for life cycle assessments. **ISO 14040** establishes the baseline structure of the study, containing four main phases : **goal and scope definition**,

life cycle inventory, **life cycle impact** assessment and **interpretation** [18], while **ISO 14044**, elaborates on methodological consistency, transparency and data quality. Following these guidelines ensures academic rigor and comparability with previous LCA studies [19].

A **cradle-to-gate** approach is adopted, thus evaluating the impacts associated from **input acquisition** to **client distribution**, including operations, chemical dosage and energy consumption, all are calculated through field visits.

3.2 Function and Functional Unit

The functional unit selected for this work is **one cubic meter ($1m^3$) of fresh water** expedited to clients, it will serve as the reference quantity throughout our work, it is both practical and physically relevant as it is standardized in water treatment system LCAs. This is a key aspect as it is considered the reference to which all other metrics are conformed to, as well as permitting comparison and benchmarking against existing literature. Additionally, it is also aligned with the **ISO 14044** norm that requires consistent reference units [19].

Nonetheless, this choice does present certain constraints, the choice of a universal functional unit does not account for the differences present in RO plants, both on the geographical and technological aspects. Geographical implications take form in variations in climate and feed water characteristics across different regions. Moreover, as scientific advancements materialize, desalination systems and infrastructures may vary, RO facilities are not equivalent and differ notably in terms of energy sources or operation modifications [20].

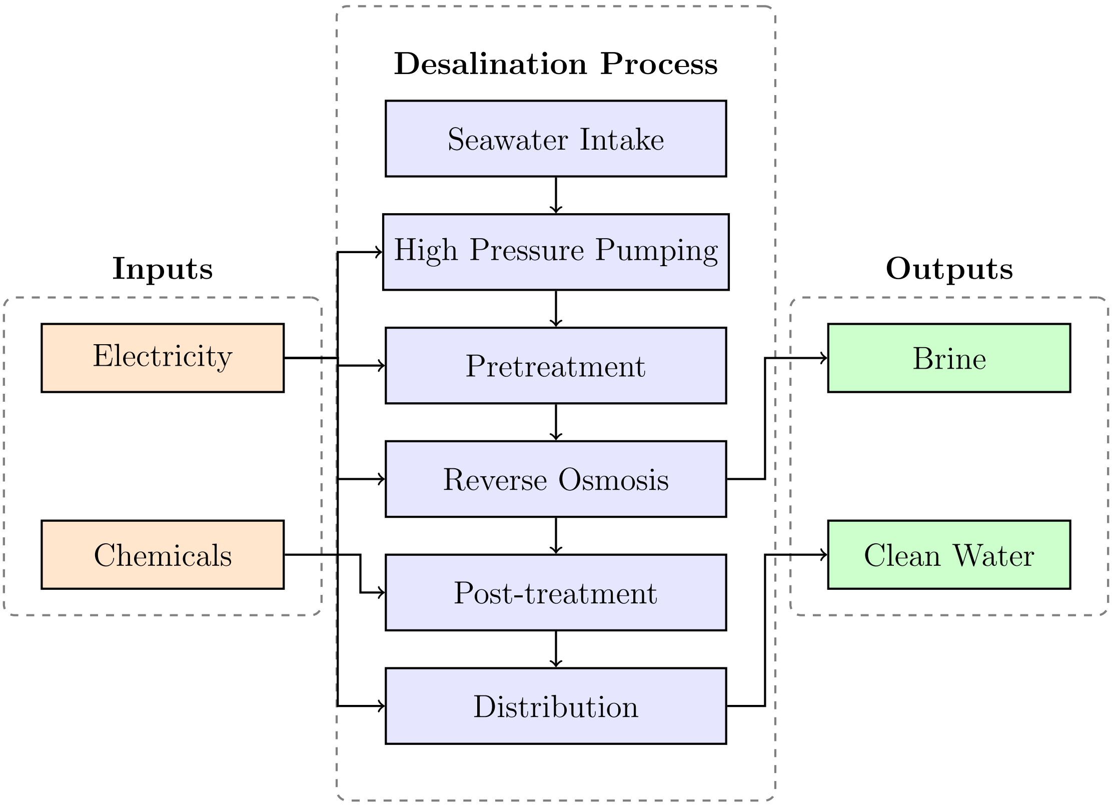
3.2.1 System Boundaries

The system boundary includes all stages of the seawater reverse osmosis desalination process within the facility, the life cycle assessment approach selected is a cradle-to-gate methodology, focusing on the production of $1m^3$ of potable water from source intake to the expedition of treated water to clients via underground pumping enclosed by the plant's perimeter, providing a thorough,comprehensive evaluation of impacts throughout the RO desalination process.This analysis focuses on the following stages:

- Seawater intake
- High pressure pumping

- Pretreatment
- reverse osmosis process (via membrane filtration)
- Membrane production and replacement
- Post-treatment (mineralization, disinfection)
- Distribution to clients
- Brine management

The primary concern of the study is **the operations phase**, membrane-related consequences are included due to their direct influence on the efficiency of the process as they perform the central role of the system, in this assessment their life cycle, from production to replacement, is evaluated.
Infrastructure, maintenance, and administration are excluded due to minimal impact(less than 5%) and data gaps, focusing the boundary on impacts per kilogram of freshwater produced [21].



System Boundary Diagram

3.3 Choice of Life Cycle Assessment Methodology

For this study, we chose **with the ReCiPe 2016 consequential Midpoint (Hierarchist) no LT method**. The midpoint level gives a more focused view on specific

impacts like emissions and toxicity, which fits well with our process-based analysis. We picked the **Hierarchist (H)** version since it's the standard and most balanced approach used in LCA studies.
As for the **no Land Transformation** option, it made sense for our case—land use isn't really relevant for desalination, and including it would've added unnecessary uncertainty. Overall, this setup helps us stay consistent with literature and gives a clearer interpretation of how shifting to 30% renewable affects the system.

3.4 Life Cycle Inventory

Table 3.1: Life Cycle Inventory

Material	**Quantity**	**Unit per m^3**
Electricity,low voltage	3.49	kilowatt hour
Limestone,unprocessed	3.5e-5	kilogram
Sand filter	2.63e-5	kilogram
Sodium hydrogen sulfite	2.37e-5	kilogram
Carbon Dioxide,liquid	1.6e-5	kilogram
Sodium hypochlorite	4.5e-6	kilogram
Polycarboxylates	6e-7	kilogram
Cartidges	1.32e-7	kilogram
Sea-water RO module	1.99617647e-10	m^2
water works, capacity 6.23E10l/year	5.35260270306436e-13	/

3.4.1 Electricity

The plant is wired to the **SONELGAZ** sector through a subterranean high voltage $63kV$ **line** as a primary source of energy along with a secondary areal line within the industrial zone. Reverse osmosis desalination is **an extremely energy consuming process**, the plant is designed to reach a $15MW$ capacity, but it's operating at 97% of that value as **the operational average observed is** $3.49kWh/m^3$.

3.4.2 Chemicals

Anti-scalant

The plant uses the commercial product **aqua 111** to prevent fouling of scaling, its exact composition remains confidential. Based on information available on the **ecoinvent 3.11 database**, it has been modeled as polycarboxylates, with a**daily consumption of 60kg**

Calcium carbonate $CaCO_3$

The water flow through calcite chambers post-treatment for mineralization, the plant uses **3 to 4 tons a day of unprocessed limestone** to adjust hardness, recover minerals lost duringRO and prevent corrosive pipes.

$$CaCO_3(s) + CO_2(g) + H_2O \longrightarrow Ca^{2+}\,2\,HCO_3{}^-$$

Carbon Dioxide CO_2

The facility is a client of ***Linde gaz***, carbon dioxide is delivered in its liquid form before going through a heat exchanger to regain its gaseous form, it is injected post-RO and has a dual function ; catalyst in the mineralization reaction and **PH-stabilizer** to ensure neutrality:

$$CO_2 + H_2O \longrightarrow H_2CO_3$$

$$H_2CO_3 \longrightarrow H^+ + HCO_3$$

Sodium Hypochlorite HoCl

It is the last step of post-treatment before expedition, NaClO's daily consumption rate is **450 kg**. It's purpose is to disinfect and prevent biological microorganism development inside pipes. The disinfection mechanism can be simplified by the following reactions:

$$HoCl \longrightarrow Cl^- + O$$

Sodium Hydrogen Sulfite $NaHSO_3$

primarily used as a security measure following the chlorination operation occurring one to two times a year. It's a de-chlorination agent that reduces chlorine according to the following reaction :

$$NaHSO_3 + HOCl \longrightarrow HCl + NaHSO_4$$

3.4.3 Filtration and Treatment Media

Pre-treatment Filters

These filters have been modeled separately, the pre-filtration subprocess has **45 filters**, each with a capacity of $130m^3$, the media contained inside has an average lifespan of **5.5 years**. The 45 entities can be divided like so:

- **25 sand filters** : containing $34m^3$ of granular silica sand with grain sizes ranging from 2 to 4 µm and $30m^3$ of anthracite coal, granular activated carbon was selected as it was the closest available alternative due to lack of specific datasets and comparative properties.
- **15 anthracite filters** : similar to sand filters with the only variable being the grain sizes ranging from 1 to 2 µm.

Table 3.2: Sand filter Activity

Material	**Quantity**	**Unit per m^3**
Activated carbon, granular	0.46875	Kilogram
Silica sand	0.53125	kilogram

Filter Cartridges

The micro-filtration sub-process is crucial for membrane protection, it consists of 10 high pressure vessels, each containing 277-280 cartridges. These cartridges filter suspended solids and impurities with diameters as little as 5 µm. For this study, filter cartridges have been disaggregated into constituent material ; **polypropylene granulate**, **silicone product**and **nonwoven polypropylene textile** which holds precedence upon other constituents.

Table 3.3: Filter Cartridge Activity

Material	**Quantity**	**Unit**
Polypropylene granulate	0.08	Kilogram
Textile, nonwoven polypropylene	0.9	kilogram
Silicone product	0.02	kilogram

3.4.4 Reverse Osmosis Membranes

The plant uses the **Hydranautics scw5-ld 8-inch spiral wound** membranes with a $400ft^2$ surface area, they are at the core of the main process ; reverse osmosis. Their lifespan under optimal condition averages **5 to 7 years** [20].

3.4.5 Model Development and Studied Scenarios

In an attempt to evaluate the environmental performance of reverse osmosis desalination, a total of **five scenarios** were established for this study with **variations in the current energy mix** as well as**system expansion through brine valorization**, but still following the same baseline inventory modeled on **Activity Browser** linked to the **ecoinvent v3.11** database with a **unified functional unit of** $1m^3$ **of produced freshwater**.

The first scenario represents **BAU**, the model has been developed following local industrial practices for desalination and the most prominent quantitative input identified by the life cycle inventory was electricity given that desalination is an extremely energy intensive process.

As of 2021, Algeria's energy grid remains dominated by hydrocarbons, with natural gas and oil contributing 64.84% and 34.63% respectively, totaling 99.47% of the power mix. With electricity demand rising and projected to hit $150TWh$ by 2030, this fossil-fuel dependency poses both environmental and energy security concerns [22]. In response, Algeria has committed to reducing GHG emissions by 7% by 2030 and launched a national renewable energy program aiming to integrate 27% renewable—mainly **solar** and **wind** into the energy mix, leveraging the country's vast solar and wind potential [23],[24].

This study explores the gradual implementation of renewable energy sources in the national grid :

- **Scenario 2 : 10% RE**
- **Scenario 3 : 20% RE**
- **Scenario 4 : 30% RE**

Electricity data was modeled with the following proportions :

- 73% solar power
- 27% wind power

In alignment with Algeria's renewable energy program's aim to primarily focus on solar power and wind power secondarily [24].

Scenario 5 explores a system expansion in which resource recovery takes form as , as this study is conducted as part of Dr K.Kerouba's project : **Dual Material and**

Energy Valorization of Reverse Osmosis Brine : A Modular Engineering Solution Adapted to the UTE Desaladora Skikda Plant.

A pilot unit (shown in 3.1)was developed to demonstrate the project's feasibility, it involves a power generator, two circulation pumps and an asymmetrical electrolyzer that contains a membrane that physically separates the anolyte, corresponding to the RO concentrate, and catholyte, the permeate, while allowing ion migration to maintain charge balance during electrolysis.

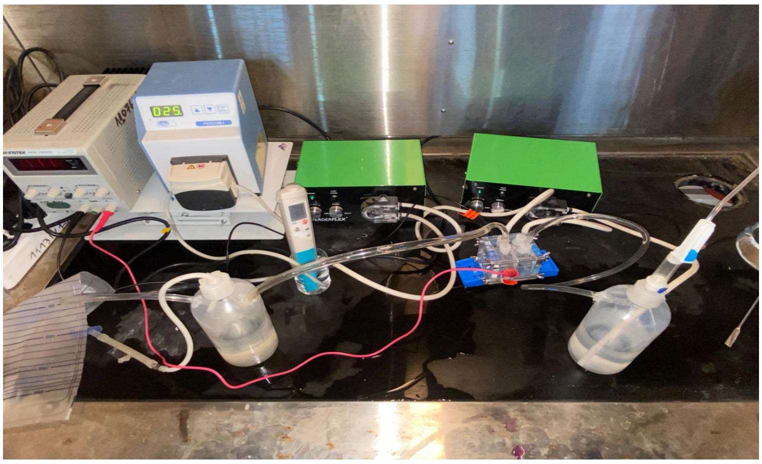


Figure 3.1: Brine Valorization Laboratory Pilot

This unit's consumed and resulting chemicals are presented in table 3.4 and 3.5

Table 3.4: Mass Balance 01 **(Consumed elements)**

Mass balance	consumed anodic H_2O	consumed anodic Cl^-	consumed cathodicH_2O
mmol/min	0,10417973	0,02289410271	0,2312535627
mg/min	1,87523514	0,8127406462	4,162564129
kg	98,01	42,48	217,56

Table 3.5: Mass Balance 02 **(produced elements)**

anodic O_2	anodic Cl_2	cathodicH_2	cathodic HO^-	formed cathodicNaOH
0,052089865	0,01144705136	0,1156267814	0,2312535627	0,005621847834
1,66687568	0,8115959411	0,2312535627	3,931310566	0,2248739133
87,12	42,42	12,09	205,47	11,75

Rq: at the working anodic pH (9), the Cl_2 is hydrolyzed and dissociated into 62.73 kg of HClO – .

This work models the industrial adaptation of the pilot unit using LCA, where hydrogen from the electrolyzer powers a fuel cell that supplies it back with electricity, forming an efficient energy loop; like the pilot setup, RO reject serves as the anolyte and treated water as the catholyte, aligning with the plant's 47–53% recovery rate.
The main byproducts targeted by the electrochemical proposed process would be **hydrogen gas(H_2)**, **Hypochlorite (HClO –)** and **Sodium Hydroxide(NaOH)**. As stated previously, hydrogen gas is valorized as an energy carrier.

Hypochlorite, produced through **secondary chloride oxydation** at the anode, has the potential to replace either partly or fully the commercial sodium hypochlorite currently used as a post-treatment disinfectant is the UTE Desaladora Skikda plant.
As for sodium hydroxide, the plant notably employs NaOH for post-treatment pH adjustment during the winter period.

In contrast, other products, such as **chlorine gas(Cl_2)** and **oxygen gas(O_2)** are not prioritized.due to chlorine's toxicity and oxygen's limited utility and natural abundance [3].
To be done, a separate 'electrolyzer' section has been modeled in activity browser, to which have been added the following activities :

- Brine : with the only input being the final product from the fifth scenario, to model valorization
- Hydrogen : producing $0.605kg$ of hydrogen gas and the following inputs :

Table 3.6: Hydrogen Activity in AB

Product	Amount	Unit per m^3
Brine	0.05	kg
Tap water	0.05	kg
Fuel cell	11.07	kWh
Electricity, low voltage	32.39	kWh

- Fuel cell : outputting 11.07 kWh

Due to software constraints limiting outputs to one per activity, hydrogen has been added to both sodium hydroxide and sodium hypochlorite activity to mimic uniform input and output flows.

Table 3.7: AB activities

Product	Amount	Unit per m^3
Fuel cell	11.07	kWh
Hydrogen gas	0.605	kg
Sodium hydroxide	0.587	kg
Sodium hypochlorite	3.13	kg

Chapter 4

Results and discussion

4.1 Energy Consumption Analysis

This energy consumption analysis is strictly limited to the **BAU** scenario, as the other cases (previously detailed in Methodology) are only defined by assumed system configuration which inevitably prevents a detailed process energy breakdown.
The plant's theoretical maximum capacity is $15MW$, the energy consumption in this case (for the production of $100.000m^3$ of potable water) will rise up to $3.6kwh/m^3$; in practice it only operates at 97% of that design capacity value, the attributed energy consumption of the BAU set up is actually $3.492Kwh/m^3$. We were unable to access exact and detailed report for energy consumption of each sub-process from the station (site specific) so we resorted to bibliographic literature for a comprehensive energy profile.

A literature based compilation of specific energy requirement for each unit operation distributed the total energy demand an RO plant accordingly [11]:

- RO separation: 71%
- Pre-treatment: 10.8%
- Brine handling, storage, maintenance, etc.: 7.6%
- Intake: 5.3%
- Freshwater distribution: 5.0%

Based on these percentages, we estimated the energy consumption of each sub process of the Desaladora RO plant for a total energy consumption of $3.492Kwh/m3$, results are summarized in the following table:

Table 4.1: Energy Consumption BAU

Sub process	Energy Consumption	Unit per m^3
RO separation	2.4793	Kilowatt hour
Pre treatment	0.3771	Kilowatt hour
Brine handling + others	0.2654	Kilowatt hour
Intake	0.1851	Kilowatt hour
Freshwater distribution	0.1746	Kilowatt hour
Total	3.492	Kilowatt hour

4.2 Environmental Impact Assessment

As per standard practice, assessing the environmental impact of a study is the third phase of a LCA, in our study for instance evaluating the potential impact of the inflows and outflows of the system was done following the certified standard 3 steps : **choice of impact categories**, **classification** and **characterization**[9]. Our study considers these three primary impact categories:

- Climate change no LT, Global Warming Potential (GWP100) no LT
- Eco-toxicity: marine no LT , marine eco-toxicity potential (METP)no LT
- Energy recourse : non-renewable , fossil no LT ,fossil fuel potential no LT(FFP)

The main argument for justifying the choice of these impacts is having a more accurate literature comparability, our simulation data will be compared against previous bibliographic results, and most articles include these configurations for assessing impact.

The GWP impact was chosen in regards to the energy intensive nature of reverse osmosis SWD, but also to assess the consequences of the country's heavy reliance on fossil fuel based electricity (expressed in **CO2 eq**), same goes for **Fossil Fuel Depletion(FFP)**, this category is widely recognized in desalination studies(expressed in **kg oil eq**)

The marine eco-toxicity metric quantifies the environmental repercussions of brine disposal on marine organisms (expressed in **kg 1,4-DCB-Eq**) ,it was selected due to the harmful effects of brine discharge from RO plants on marine life. Studies show that high salinity and chemical residues can cause toxicity in benthic species and disrupt local ecosystems [6].

For classification, the LCI result data are sorted out by environmental concerned each element is assigned to one or more of the impact categories mentioned earlier. In the characterization step each element's flow is multiplied by its characterization factor and this according to the following equation [9] :

$$\sum_i (elementflow_i * characterizationfactor_i)$$

These two steps are performed automatically once the calculation process runs.

4.3 Interpretation

The fourth and last step of the standardized LCA approach is interpretation, in this phase the results from the inventory and impact assessment are presented and analyzed through an environmental lens in order to identify the most impactful stages of the desalination process. The figure below shows the assessment results of the 05 desalination scenarios (explicitly detailed in the previous chapter and represented in rows in the figure4.1) ; each scenario's 1 m^3 output of tap water is evaluated for 04 impact categories (represented in the chart's columns):

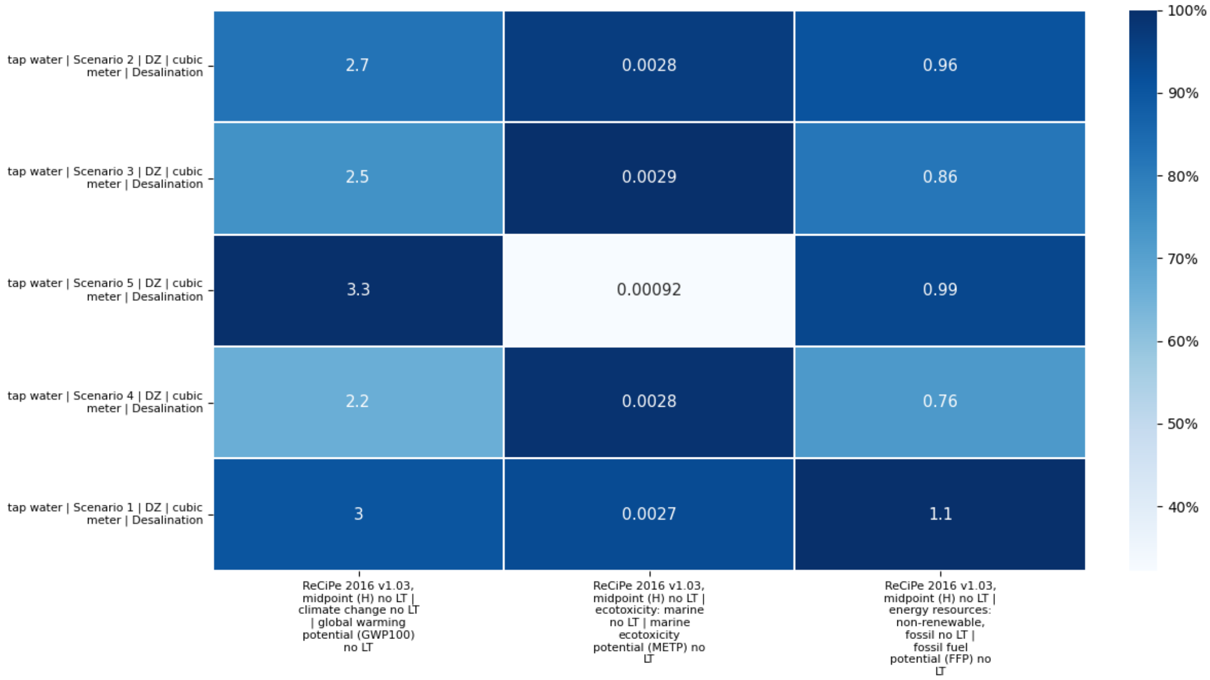


Figure 4.1: LCA Results

The color bar ranging from deep blue to lighter shades of gray, helps to visualize the intensity of each impact ; numerical comparison of data will be further detailed.

The BAUscenario represents the baseline case of our study, and is treated as a reference point for this analysis to showcase the environmental benefits or drawbacks of the other scenarios.

For each of the three impact categories, we will first compare all five scenarios against one another, then carry out a detailed process contribution analysis to identify the key drivers of impact.
Under process contribution, **Cut off level** is a user defined minimum limit that's set to filters out results and keep the contribution analysis clear and simple, any process whose impact contribution falls below the cut-off level will be hidden and instead grouped into "others".
For each case, we adjusted the relative cut off level to best highlight the main impact drivers for easier interpretation, each scenario is now identified by its numeric label :

Table 4.2: General Definitions

New name	Scenario 01	Scenario 02	Scenario 03	Scenario 04	Scenario 05
Description	BAU	BAU+10%	BAU+20%	BAU+30%	BAU+expansion

4.3.1 Global Warming Potential (GWP100) no LT change impact (GWP 100 no LT)

This category measures the total greenhouse gas emissions expressed in **kg CO_2equivalent**, the scenarios exhibits the following data :

- Scenario 01 records a moderately high value of**3 kg of CO_2 eq**, this suggests a considerable environmental burden and could be explained by the total dependence of the station on fossil-fueled energies.
- GWP falls to **2.7 kg CO_2** eq in the 2nd scenario, this limited contribution of renewable energy delivers only a modest drop in emissions.
- The third and fourth assumed scenarios produce the least amount of Co_2 : **2.5 and 2.2 kg CO_2eq per meter cube respectively** ; this is directly linked to the progressive implementation of renewable energy in the inventory.
- In contrast, the last scenario scores higher, 1 m^3 of tap water produces **3.3 kg CO_2 eq** which slightly exceeds our reference baseline, this is a clear indicator of the energy intensive nature of the brine valorization process in system expansion (earlier referred to in chapter 3).

The processes contributing to each scenario'sGWP are shown in the horizontally stacked colored bar chart 4.2 providing a comprehensive breakdown (relative share in%) that presents different origins of the total impact across the full life cycle of the systems.

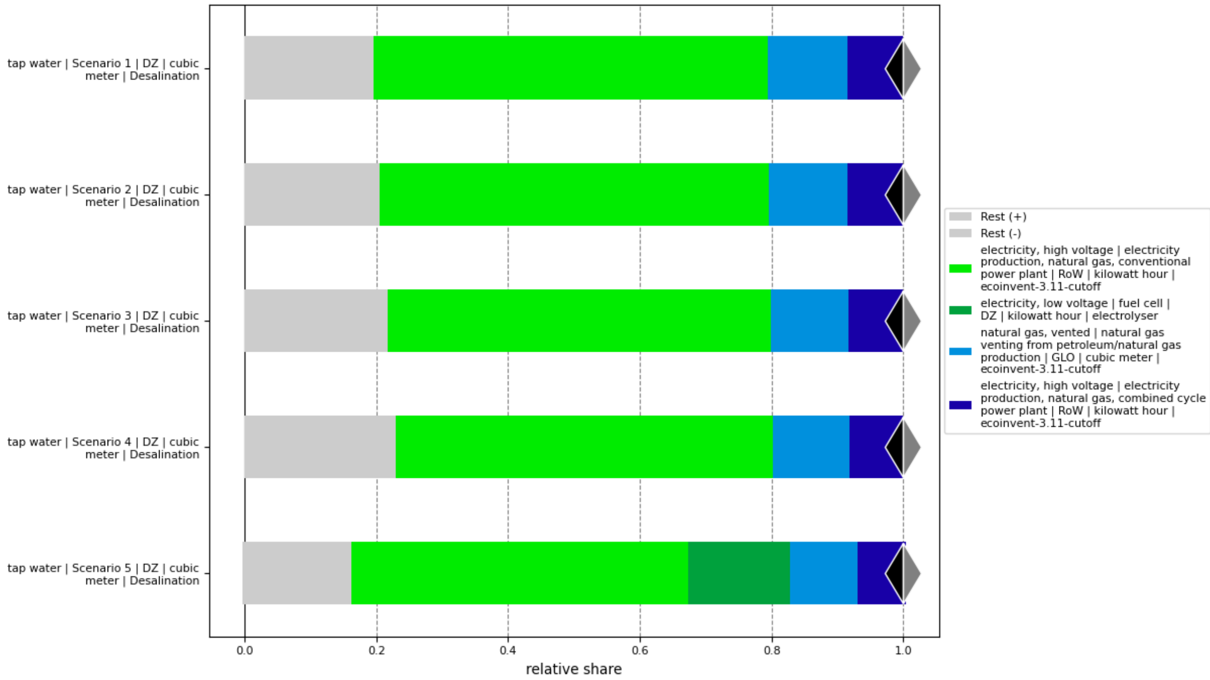


Figure 4.2: GWP Results

As observed in figure4.2, **electricity is the prominent burden source** in all of the first 04 studied scenarios it contributes with approximately **72% in the total impact** , this includes several processes related to power grid electricity production ,**natural gas** is the **second major contributor** and is **responsible for 12% of the impact** As for scenario 05 , the result slightly differ but follows the same pattern , the electrical contribution rises up to 73% ,15% of that attributed to the fuel cell activity. in this case, the natural gas accounts for 10% of the result. The remaining processes represented in grey are relatively minor.

4.3.2 Energy Resource : non-renewable , fossil no LT ,fossil fuel potential no LT(FFP)

This impact quantifies the consumption of finite fossil fuel energy resources (crude oil ,natural gas or hard coal) associated with our 05 studied scenarios it is expressed in terms of **kg-oil equivalent** ; results are as follows :

- The BAU detains the biggest impact with a value of **1.1 kg oil-eq** , this was highly anticipated because the station doesn't rely on non-renewable energy resources , trailing by is scenario 5 producing **0.99 kg oil-eq** ,this small margin reflects their greater demand on non-renewable reserves

- In contrast, the fourth scenario has the least impact with **0.76 kg oil-eq** this is mainly driven by the assumed 30% share of green energies

- Scenario 2 and 3 show consistently lower results and exhibit these respective values: **0.86** and **0.76 kg oil-eq** , in both cases the decrease compared to scenario 01 is primarily resulting from the substitution of part of conventional grid power with sustainable energies

Similarly, to the previous impact, here is a breakdown of the total impact into process specific fragments:

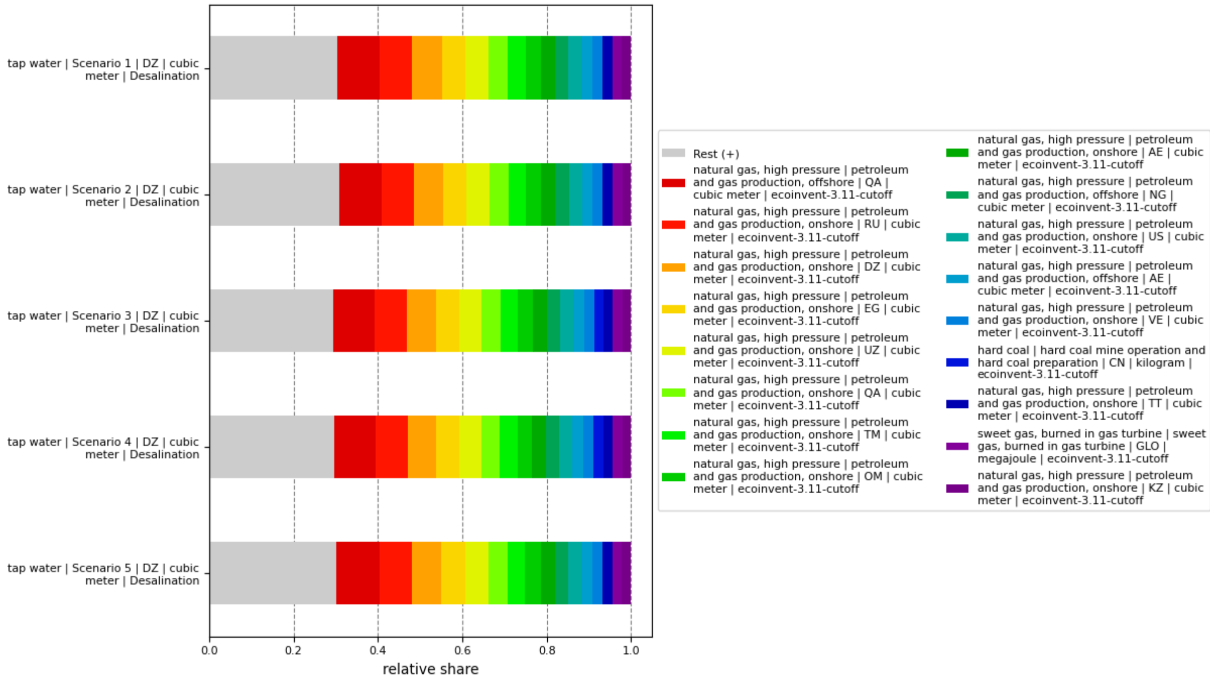


Figure 4.3: Fossil Fuel Depletion Results

Figure 4.3 shows a high level of detail in the process contribution ; roughly 18 different processes are assessed and are all variants of **natural gas** , the main takeaway is that the cumulative impact of each natural gas sub process is significantly greater than any other individual process, it **accounts for 76% of the total impact** As a consequence, the non-renewable energy depletion is driven by natural gas extraction processing and transport processing .

4.3.3 Eco-toxicity : marine no LT , marine eco-toxicity potential (METP)no LT

This assessment category indicates the potential harm to the oceanic life by the release of toxic chemicals related to our activities , it is referred to in **kg 1,4-DCB-Eq**, the outcomes are compiled as follows :

- 2nd 3rd and 4th scenarios can be a grouped under the same category as their impacts is closer in magnitude and ranges from **0.0028 to 0.0029 kg 1,4-DCB-Eq**; the BAU scenario is next in rank and outputs **0.0027 kg 1,4-DCB-Eq**

- The previous group shows slightly higher marine eco toxicity which comes from manufacturing and installing renewable energy systems that release toxic substances ; whereas BAU avoids extra impacts by only relying on local infrastructure.

- The **fifth scenario** is notably the least harmful on the marine life,it **yields only 0.00092 kg 1,4-DCB-Eq** which is **10 times smaller** than the rest, this comes from the conversion of waste brine that usually is disposed of in the sea into usable chemical substances

The next section provides a detailed overview of how each process impacts the final output:

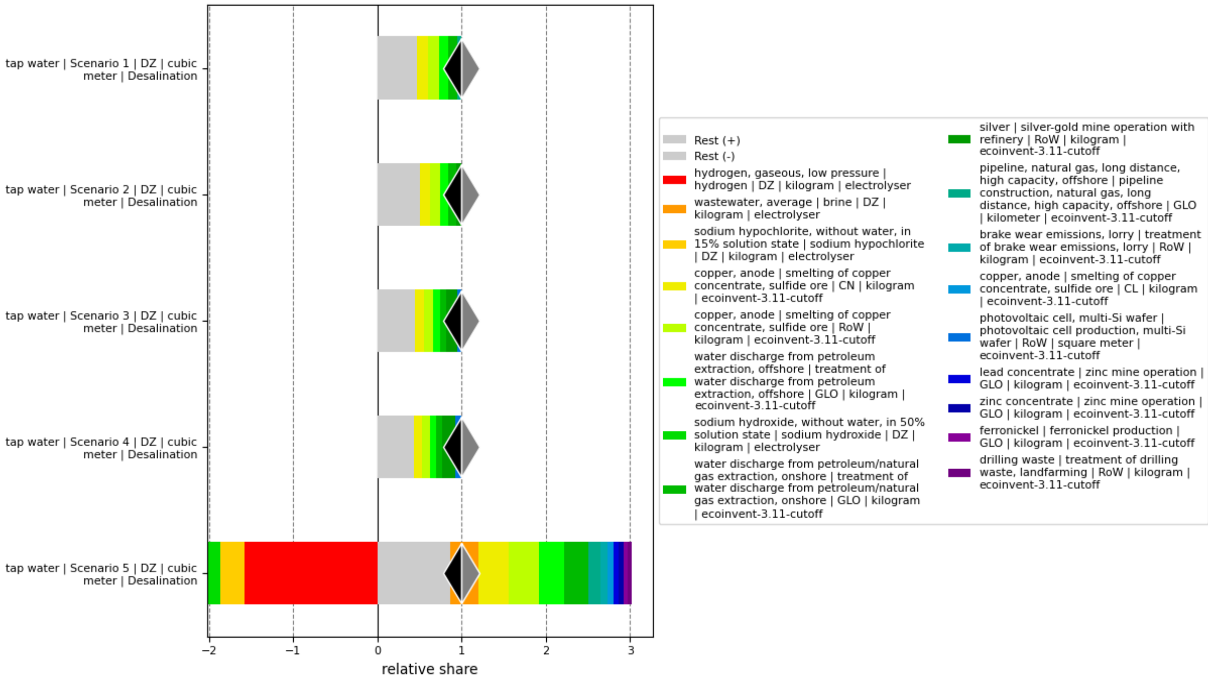


Figure 4.4: Marine Eco-toxicity Results

- The four first scenarios share almost identical patterns of impact distribution across the processes, each sub-process contributes in equal measures this includes the following activities:smelting of copper concentrate, water discharge from petroleum/gas extraction, sodium hydroxide and mining operations.

- scenario 04 exceptionally accounts for a minor photovoltaic cell input that this adds on the impact's weight.

- Scenario 05 stands out with significant negative impact processes that come from the recovery of ;hydrogen, sodium hypochlorite and sodium hydroxide derived from the electrolyzer. This leads to a cumulative negative contribution of -2 units that will help in balancing out the positive +3 units impact from the other processes of the system.

- The negative processes are quantified in percentages as follows : 16%for NaOH28% for hypochlorite and 150% of hydrogen ; these considerably high values provide substantial environmental credits, i.e. avoided burdens, because they could eventually replace the original products in the classic BAU inventory.

- As for the positive processes contribution, we see in the figure4.4 that the impact is distributed fairly evenly among them 16 sub-process that include various mining ,waste treatment and energy related activities.

4.4 Key Takeaways and Benchmarking

- Our cradle to gate analysis confirms that introducing renewable energy improves the environmental impact in general ,the increasing integration of PV+wind systems in scenario 02, 03 and 04 steadily reduce the carbon footprint and leads to lower fossil fuel use , we achieved a reduction of 8% of Co_2emissions compared to the conventional BAU scenario.

- The group performs less favorably in eco-toxicity due to upstream impacts from manufacturing and deploying renewable technologies like solar panels and wind turbines.

- the 5th scenario outperforms all in terms of marine eco-toxicity, brine valorization though only based on a hypothetical up-scaling significantly reduces harmful discharge, this comes with a trade off as the same scenario shows the highest GWP impact because of the energy-intensive nature of the process.

- The BAU scenario is at the forefront in fossil depletion as a consequence of its continued reliance on finite energy resources, but still but scores moderately in the other impacts.

- Electricity related activities burdens the environment most since they have an important share in the total impact across all studied scenarios.

4.4.1 Literature comparison

- The selection of appropriate benchmark studies was challenging for two main reasons : first limited access to recent article as most recent studies on larger scale desalination plants aren't open access, and second the available open source access predominately address small scale facilities.

- However, the compiled studies in table are the most relevant and accessible options for comparison because they use the same functional unit **($1m^3$ of tap water)** have a comparable Life Cycle Inventory and apply the same impact categories[26]:

Table 4.3: Benchmarking of Results

Scenario/Impacts	GWP(kg CO2 eq)	FFP(kg-oil eq)	ECO(kg 1,4-DCB-Eq)
BAU	3	1.1	0.0027
BAU+10%	2.7	0.96	0.0028
BAU+20%	2.5	0.86	0.0029
BAU+30%	2.2	0.76	0.0028
BAU+ sys expansion	3.3	0.99	0.00092
Fayazz 2023	3.4	1.2	0.039
Tarpani 2021	7.5	0.217	0.0121
Abdulghani 2021	2.6	0.002	0.004

- The findings of the 5 studied scenarios are for the most part in the same range as those in comparable studie.

- One exception is for fossil fuel depletion category which shows higher scores even with PV and wind integration.

Conclusion

This work provided a comprehensive environmental assessment of seawater desalination using the Life Cycle Assessment approach. We have evaluated how energy configurations and system improvements influence the environmental footprint through scenario modeling, taking the UTE Desaladora plant in Skikda as an example. The results confirmed that integrating renewable energy, especially solar and wind, leads to noticeable reductions in carbon emissions and fossil fuel dependency. However, the manufacturing of renewable technologies causes a trade-off, particularly in marine toxicity.

The fifth scenario, which explores brine valorization, shows promise for future integration, offering a circular economy approach by recovering chemicals and energy from waste streams. Yet, its energy-intensive nature emphasizes the importance of balancing innovation with durability. Overall, this study emphasizes that while desalination is a vital solution in water-scarce regions, its sustainability depends heavily on the choices made in system design and energy sourcing.

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