AMERICAN UNIVERSITY OF BEIRUT

LIFE CYCLE ASSESSMENT OF SEAWATER REVERSE OSMOSIS PLANT POWERED BY FOSSIL FUELS VERSUS RENEWABLE ENERGY

by
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A thesis
submitted in partial fulfillment of the requirements
for the degree of Master of Science
to the Bahaa and Walid Bassatne Department of Chemical Engineering and Advanced Energy
of the Faculty of Engineering and Architecture
at the American University of Beirut

Beirut, Lebanon
December 2019

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ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my advisor Dr. Mahmoud Al-Hindi for his continuous guidance, patience and motivation throughout all the time of research and writing of this thesis. He continuously steered me in the right direction, pushed me to perform better and encouraged me in this learning process.

I would also like to thank Dr. May Massoud and Dr. Walid Saad for agreeing to be on the committee for this project and for reading and reviewing this report.

My genuine appreciation also goes to my friends and family who have unfailingly and continuously supported and encouraged me throughout the entire process.

AN ABSTRACT OF THE THESIS OF

Elena Najjar for Master of Science
Major: Chemical Engineering

Title: Life Cycle Assessment of a seawater reverse osmosis plant powered by fossil fuels versus renewable energy

Coupling seawater reverse osmosis with renewable energy such as PV and wind is an active research area and understanding the environmental impact of these integrations using the Life Cycle Assessment (LCA) tool is a major concern for many communities.

The aim of this study is to investigate the LCA of several renewable energy alternatives coupled with Seawater Reverse Osmosis (SWRO) for a small/medium town in remote areas and quantify the environmental impact reductions that can be achieved when powering this plant with electricity from biogas from Anaerobic Digestion (AD), PV and wind. To do so, a 4500 m^3*/day SWRO plant based in Lebanon was designed using WAVE software and each of biogas, PV and wind plants were designed using HOMER Pro. The LCA was performed using Simapro PhD version 9 and IMPACT2002+ impact assessment method was used.*

Results show that the most optimal integration is with wind energy because the highest environmental impact reductions were achieved in most categories. However, both biogas and PV did prove to have significant improvements compared to conventional fossil fuels.

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CHAPTER 1

INTRODUCTION

Water security refers to allowing access to safe and clean water for everyone to satisfy humans' basic needs (Xiao-jun *et al.,* 2014). With the rapid increase of the human population and the even more accelerated increase in freshwater demand, pressure on this natural resource is increasing and thus limiting the ability to achieve global water security (UNESCO WWAP, 2019). As a result, water scarcity is diffusing to many parts of the world, even ones that have not previously suffered any water shortages (Xiao-jun *et al*., 2014). One of the approaches adopted to overcome water scarcity is desalination (Ganora *et al.,* 2019).

1.1.Desalination

Desalination refers to separating saline water (seawater or brackish water) into freshwater and brine which is usually dumped into the sea or discharged to sewers or surface water. There are two types of desalination technologies: thermal and membrane.

1.1.1. Types of desalination

i. Thermal desalination

Thermal desalination is based on phase change where evaporation separates salts from water. It reduces the vapor pressure of water in every unit, so that boiling can occur at lower temperatures as the flow moves from one effect to another (El-Dessoukey & Ettouney, 2002). This process consumes large amounts of thermal energy and to a lesser extent electricity. Different types of thermal technologies like multi-stage flash (MSF) and multi-effect distillation (MED) are commonly used in industry.

ii. Membrane desalination

Membrane technologies are based on adsorbing dissolved solids in the water onto semi permeable membranes that operate by electric pumps requiring a high amount of electricity and no thermal energy (Gude *et al.*, 2010). Reverse osmosis (RO) and Electrodialysis (ED) are the most commonly used membrane technologies. The concept behind RO is to create a pressure difference across a set of membranes higher than the osmotic pressure of the water. ED allows salt ions to migrate by applying an electric current across the membrane (El-Dessoukey & Ettouney, 2002).

1.1.2. Desalination energy requirements

Desalination is very energy intensive and different types have different energy requirements. Thermal desalination requires thermal energy for evaporation and electrical energy for pumping of feed and product water. Membrane desalination, however, requires only electrical energy for membrane separation and pumping of feed and product water. Typical energy consumption values and GHG emissions for the most commonly used technologies are found in table 1 (Gude *et al.*, 2010).

Table 1 Specific energy consumption and GHG emissions of desalination technologies

Classification	**Technology**	**Thermal energy (kJ/kg)**	**Electrical energy (kWh/m^3)**	**Total energy consumption (kWh/m^3)**	**Greenhouse gas emissions (kg CO$_2$/m^3)**
Thermal	MED	150-220	1.5-2.5	8-20	19.2
	MSF	250-300	3.5-5	15-25	24
Membrane	RO	-	5-9	5-9	8.6
	Electrodialysis	-	2.6-5.5	2.6-5.5	5.3

Electricity consumption has increased with the global increase in desalination capacity and the reason behind this is attributed to the shift from thermal to membrane technologies, more specifically RO. As a result, high fossil fuel consumption has led to significant environmental impacts and consequently, many attempts have been done to power desalination with renewable energy (RE). In that event, researchers have applied the Life Cycle Assessment (LCA) tool to understand the environmental impact of desalination. Among the RE technologies that have been coupled with desalination, solar and wind energy have, to date, proven to be the most successful from an environmental point of view. The present work suggests a novel integration which consists of powering a seawater reverse osmosis (SWRO) with electricity from biogas as a result of anaerobic digestion (AD). The aim of this study is to determine whether this integration will achieve a more significant reduction in environmental impact than wind and solar photovoltaic (PV). Accordingly, a comparative LCA is performed on a designed SWRO with different power sources: Lebanese electricity grid, wind energy, solar PV, and biogas.

The following report consists of five chapters. Chapter two is a literature review that covers the LCA tool and provides an overview on previous LCAs on desalination. Chapter three describes the methodology followed in this research and the software used for designing the RO plant, RE systems and for performing the LCA. Chapter four discusses the results that were obtained for the specific case study. Finally, chapter five concludes by presenting the main findings of this work and providing recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

The following chapter discusses the LCA methodology as described in ISO14040 series and the main steps it adopts. It then summarizes some LCA studies done on desalination powered by fossil fuels and renewable energy.

2.1. Life Cycle Assessment (LCA)

LCA is a tool that quantifies the environmental performance of a product or service across its entire life cycle, from raw material acquisition up to final disposal such as material recycling or reuse. LCA bears many applications, most importantly identifying environmental hotspots in a product's life cycle for the purpose of improving product performance. The principles and framework of LCA are discussed in ISO 14040 and ISO 14044 which detail the four main phases to be applied, whose relationship is shown in figure 1.

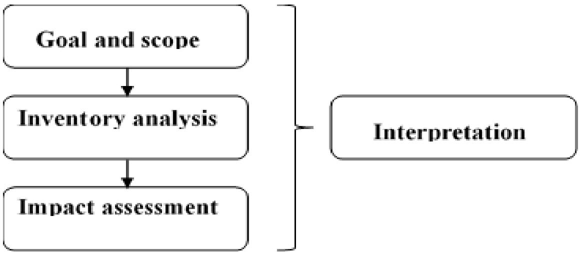

Figure 1 Stages of an LCA

2.1.1. Goal and scope

The goal of an LCA clearly describes the purpose of the study, the target audience and the intended application. The scope includes a number of definitions which are described below.

i. Function, functional unit and reference flow

The scope defines the function of a product. In cases where a single product fulfills multiple functions, the chosen function goes in line with the goal and scope. The functional unit is a quantification of the function, to which the inputs and outputs are standardized to facilitate product comparisons. The reference flow is the amount of product needed to satisfy the functional unit (ISO14044, 2006). For example, if the function of the studied product is to provide potable water for consumption, the functional unit can be expressed in volumes of potable water produced and the reference flow in volumes of water to be treated.

ii. System boundaries

The system boundary defines which inputs and outputs are included in the system. Certain life cycle stages or processes that do not impact the overall conclusion of the study can be omitted, but their omission should be clearly justified. The system boundary is defined based on cut-off criteria which can be of three types: mass, energy and environmental significance. The chosen cut-off criterion requires the exclusion of processes that contribute less than a certain percentage of the overall mass, energy or environmental impact of inputs. A sensitivity analysis can be performed, in an iterative procedure, to determine their significance (ISO14044, 2006).

iii. Impact assessment methods and categories

Impact categories, category indicators and chosen LCIA methods are defined in the scope. Impact categories are environmental issues of concern like climate change, acidification, ecotoxicity, land use and others. Category indicators are quantifications of the impact categories that express how much the studied product is impactful in a certain environmental area. Different LCIA methods have been developed based on statistical and mathematical models. They differ in the tackled impact categories and the factors used to determine the category indicator. Further description of these terms will be given in the LCIA section of this report (ISO14044, 2006).

iv. Source of data

The data representing the inputs and outputs can be collected either through communication with industry, i.e. specific production sites or from literature. Most LCA studies usually include both measured and calculated/estimated data (ISO14044, 2006).

2.1.2. Life Cycle Inventory (LCI)

LCI involves data collection regarding the defined inputs and outputs where these are quantified and allocated into material and energy inputs, products and co-products, emissions to air, water or soil, and waste. Data is validated by performing mass and energy balances on the considered unit processes. After data collection, the values of inputs and outputs are standardized relative to the chosen functional unit to facilitate comparisons. Data can be aggregated if inputs result in the same environmental impact. In an iterative procedure, the system boundaries can be refined if a sensitivity analysis proves that some inputs/outputs or even life cycle stages lack significance, or that additional unit processes must be included (ISO14044, 2006).

2.1.3. Life Cycle Impact Assessment (LCIA)

LCIA transforms the information collected in the LCI into environmental impacts by associating the inventory results into impact categories. Some terms essential for understanding LCIA are defined below.

Impact categories: environmental issues of concern to which LCI results are assigned. They are classified into midpoint and endpoint categories depending on which stage of the cause-effect chain they tackle. For example, the release of a chemical in groundwater will have as endpoint effect, the extinction of species in a lake, whereas its midpoint effect might be the increased concentration of that chemical in lake water.

Some midpoint categories include ozone depletion, ionizing radiation, ecotoxicity, fossil depletion and others. These categories are also referred to as problem-oriented categories because they take up primary chemical and physical changes in the cause-effect chain and the results represent contributions to different environmental problems. Endpoint categories, however, are aggregated into four areas of protection: natural resources, human health, climate change and ecosystem quality. They are referred to as damage-oriented approaches because they represent the final damages caused. Endpoint categories are easier to communicate to an audience that is not an expert in the field.

Category indicator: quantification of the impact category.

Characterization factors: factors derived from characterization models which are used to convert an LCI result to the unit of the category indicator. They are obtained based on scientific analysis and quantitative models, and they vary from LCIA method to another due to differences in localities and energy mixes.

An example is given below to clarify the above terms and how they are used in LCIA.

Impact category: Climate change

LCI results: amount of GHG/functional unit (for all GHG contributing to climate change)

Characterization model: Intergovernmental panel on climate change (IPCC)

Category indicator: Infrared radiative forcing (W/m2) which is a proxy for potential effects on climate, depending on the integrated atmospheric heat adsorption caused by emissions and the distribution over time of the heat absorption.

Characterization factor: Global warming potential (GWP) for each greenhouse gas (kg CO2 equivalents/kg gas)

Category indicator result: kg of CO2 equivalents/functional unit.

Example: A GWP of methane = 100 implies that 1 kg of methane has the same impact on climate change as 100 kg of CO2.

Because of the complexity and diverse nature of LCIA, different methods exist and they differ in the impact categories that they tackle and the characterization model developed. Some of the most commonly used methods will be detailed in appendix A.

LCIA involves obligatory steps which are definition, classification and characterization of impact categories, as well as optional steps which are normalization, grouping and weighting and these steps are applied in the order in which they were listed as viewed in figure 2 (ISO14044, 2006).

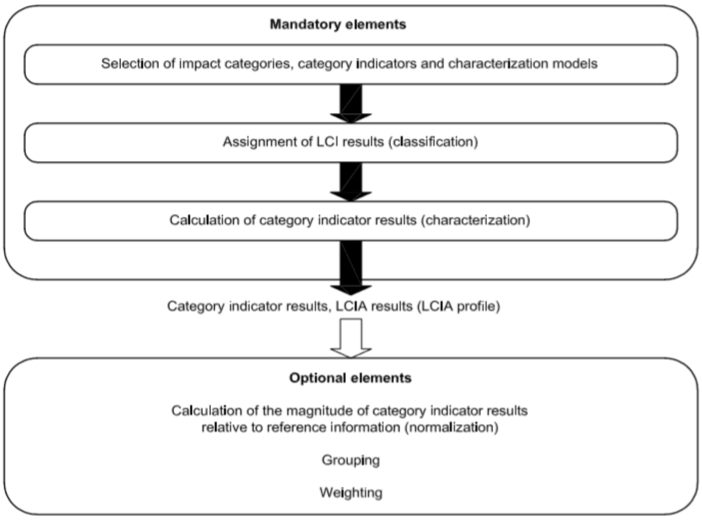

Figure 2 Elements of LCIA (ISO14044, 2006)

2.1.4. Interpretation

In interpretation, the results obtained in both the LCI and LCIA are correlated and interpreted in accordance with the goal and scope. Doing so allows identification of significant issues so that conclusions can be drawn and recommendations given on how to improve the considered product system. Interpretation may involve completeness, sensitivity and consistency checks to enhance confidence in the results.

2.2. LCAs on desalination

Many LCAs have been performed on desalination powered with fossil fuels and RE. Gude *et al*. (2010) provide an overview of the state-of-the-art combinations of RE with desalination and discuss the possibility of future integrations to provide clean water in a more sustainable and economic way. Tables 2 and 3 summarize some of the LCAs in the literature whereby different plant capacities and LCIA methods are considered. Results show that REs that have so far been integrated with desalination consist of PV, wind, hydro-power and solar thermal, and they have shown significant reductions in environmental load. All studies agree that the major contributor to the load is electricity consumption when operating on fossil fuels; however, when shifting to RE, the load shifts to either chemical use or plant construction (Shahabi *et al*., 2013).

2.3. Integration with waste to energy

Using waste to generate energy has recently gained more popularity as many countries face waste disposal problems. For countries with water shortage issues, integrating waste-to-energy with desalination could be a viable, environmentally friendly solution. Udono & Sitte (2005) developed a model for simulating a 20,000 m^3/day SW desalination plant powered by waste incineration and concluded that the current waste generation rate is capable of producing twice the electricity needed for the plant. Dajnak & Lockwood (2000) have demonstrated that combining existing MSW incineration with desalination can satisfy more than half the daily per capita water demand. They further discuss the possibility of integrating other waste transformation processes such as pyrolysis and gasification for additional economic and environmental benefits. Kang & Yuan (2017) point to evident CO_2 emission reductions with the use of anaerobic digestion (AD) technologies for waste transformation. No study has considered the possibility of coupling biogas production from AD to power desalination. Accordingly, the purpose of the present work is to design a standalone AD plant and use it to power a SWRO plant, then determine the environmental impact of such an integration to identify whether it is viable from an environmental perspective and check how it compares to fossil fuels, wind and PV.

Table 2 LCAs on desalination powered with fossil fuels

	Desalination		Life Cycle Assessment							
Reference	**Technology used**	**Capacity (m3/day)**	**LCA software**	**Goal & Scope**	**LCIA method**	**Impact categories**	**Functional unit**	**Location**	**Time**	**Results**
Raluy *et al.* (2004)	MSF (SW)	45,500	Simapro 5	Comparison of MSF, MED, RO integrated with different energy production systems	CML 2 baseline 2000	1,2,4,5,7,8,9,13	45,500 m3/day with 8000 hr of operation/yr over 25 years	Spain	25 years	*Most pollutant: coal *Least pollutant: Natural gas *Higher efficiency of energy production system decreases emissions *Integration with energy production: reduction in environmental load *RE: 80-85% reduction
	MED (SW)	45,500			Eco-indicator 99					
	RO (SW)	45,500			Ecopoints 97					
Raluy *et al.* (2006)	MSF (SW)	45,500	Simapro 6	Comparison of MSF, MED, RO	CML 2 baseline 2000	1,2,4,5,7,8,9,13	45,500 m3/day with 8000 hr of operation/yr over 25 years	Spain	25 years	*Highest environmental load: operation phase *Most pollutant: MSF (in all methods) *Least pollutant: RO (in all methods) *Highest contribution: fossil fuels impact category
	MED (SW)	45,000			Eco-indicator 99					
	RO (SW)	46,000			Ecopoints 97					
Munoz & Fernandez-Alba (2008)	SWRO	20,000	Simapro 7	Comparison of BWRO and SWRO	CML	2,4,6,7,9, Brine TDS concentration	1 m3 desalinated water	plant from Raluy *et al*	25 years	*BWRO preferable over SWRO (environmentally) *Major contribution: electricity demand (95% of total in all categories except human toxicity)
	BWRO							Almeria, Spain		
Zhou *et al.* (2011)	BWRO	10,000	Simapro 7.1	Comparison of LCIA approaches in BWRO applications	CML 2 baseline (generic) TRACI (US specific)	1-8	1 m3 desalinated water	US	entire lifetime	*Impact categories results: -Agreement between methods: 2,3 due to large spatial or time scales -Agreement between methods: 7 due to 2 contradicting factors compensating each other
Zhou *et al.* (2011)	BWRO	10,000	Simapro 7.1	Comparison of energy production alternatives in BWRO applications	CML 2 baseline 2000	1-8	1 m3	US, Singapore (SG), Spain (ES)	entire lifetime	*Lowest impact in most categories: SG (due to natural gas) *Highest impact in most categories: US (due to coal and lower power plant efficiency than ES) *Highest contribution for all scenarios: operation (electricity, antiscaling, membranes)
Beery *et al.* (2012)	UF SWRO		Developed software	Calculation of carbon footprint of SWRO	IPCC 2007	2 (only CO2)	1 m3 treated water	Dubai Palm Jumeirah	30 years	*Carbon footprint: 2.26 kg CO2 eq/m3 *Major contribution: electricity consumption (74%)
Del Borghi *et al.* (2013)	**Total water supply:** 5 purification plants & 3 SW			Comparison of water supply systems in 2009 & 2010	EPD	1-3,6-9, waste production	1 m3 treated water	Sicily, Italy	1 year	*Highest contribution : desalination plants (in all considered impact categories) *Mainly related to electricity consumption and thermal energy *Most relevant impact categories: global warming potential, non renewable energy sources, water consumption
	5 MSF units, 1 RO	80,000								
	TVC-MED	36,000								
	MVC	5000								

Where 1: Resource depletion, 2: Climate change, 3: Ozone layer depletion, 4: Human toxicity, 5: Ecotoxicity, 6: Photochemical oxidation, 7: Acidification, 8: Eutrophication, 9: Energy use, 10: Ionizing radiation, 11: Land use, 12: Odor, 13: Particulate matter/respiratory inorganics.

Table 3 LCAs on desalination powered with RE

	RE Desalination			Life Cycle Assessment							
Reference	**Technology used**	**RE technology**	**Capacity (m3/day)**	**LCA software**	**Goal & Scope**	**LCIA method**	**Impact categories**	**Functional unit**	**Location**	**Time**	**Results**
Raluy *et al.* (2005)	MSF,MED, RO (SW)	PV	45,500	Simapro 6	Environmental impacts of MSF, MED, RO integrated with RE	CML 2 baseline 2000 Eco-indicator 99 Ecopoints 97	1,2,4,5,7-9,13	45,500 m3/day with 8000 hr of operation/yr over 25 years	Spain	25 years	*Highest impacts: PV *Highest reduction: Hydro-power *Highest decrease (RE vs fossil fuels): CO2 emissions *Lowest decrease (RE vs fossil fuels): SOx emissions (MSF & MED) *Best figures (for RE): EI99
	MSF,MED, RO (SW)	Solar thermal	45,500								
	MSF,MED, RO (SW)	Wind	45,500								
	MSF,MED, RO (SW)	Hydro-power	45,500								
Wahidul K. Biswas (2009)	SWRO	Fossil fuels (grid)		Simapro 7	Comparison of fossil fuels SWRO to RE SWRO	Australian GHG method developed by RMIT	2 (GHG)	1 GL treated water	Bunbury, Western Australia		*Fossil fuels: 3,894 ton CO2 eq /GL *100% Wind: 367 ton CO2 eq /GL *Highest emissions: fossil fuels *Highest contribution: operation
		Wind									
		Fossil fuels (grid) + wind									
Jijakli *et al.* (2011)	Solar still		1.25	Simapro 7	Comparison of desalination based alternatives for water supply	Eco-indicator 99	1-5,7,8,10,11,13	1250 L/day	UAE	20 years	*Lowest impact: PV-RO *Largest impact: alternate between solar still and SWRO depending on impact category *Energy source for SWRO has significant impact on results *Solar still tank material has significant impact on results
	BWRO	PV	1.25								
	SWRO	Fossil fuels	45,000								
Salcedo *et al.* (2012)	SWRO	Solar collector + Rankine cycle	50,000	Manual	Environmental impact of desalination integrated with RE	CML 2001	2 (GHG)	1 m3 treated water	Tarragona, Spain	entire lifetime	*Economic and environmental performance are inversely proportional *Higher solar collector area, better performance *27.6% CO2 emissions reduction
Shahabi *et al.* (2013)	SWRO	Fossil fuels	137,000	Simapro	Comparison of desalination plants powered by fossil fuels to those powered by RE	IPCC 2007	2 (GHG)	1 m3 treated water	Perth, Western Australia		*Fossil fuels: electricity in operation phase more than 92% of GHG emissions *RE: chemical use in operation phase 60%, construction 17% * Fossil fuel: 90% higher emissions than both RE plants *Wind + PV: 1% higher than 100% wind
		Wind									
		92% wind 8% solar PV									
Karvounis Panagiotis (2017)	SWRO	Fossil fuels (diesel)	1200		Comparison of embodied energy and embodied CO2 of SWRO by diesel engine (DE) and wind turbine (WT)		Embodied energy (EE), Embodied CO2 (EC)	1 m3 treated water	Greek islands	1 year	*Embodied energy: - Manufacture: WT > DE -Operation: DE > WT *Embodied carbon: - Manufacture: DE > WT -Operation: DE > WT (0 emissions)
		Wind	1200								
Al-Kaabi & Mackey (2019)	SWRO	NG	175,000 275,000	Gabi	Quantification of impacts for open intake vs. subsurface intake and of different energy sources	CML 2001	1,2,3,4,5,7	1 m3 treated water	Arabian gulf		*Subsurface intake had lower impacts than open intake for both plants *PV is significantly better in GWP, NG is an equal or better performer in other categories --> need to prioritize environmental impacts of greatest concern *HFO had the worst performance
		PV									
		HFO									

Based on what has been studied in the literature, it was determined that there is a need to identify new RE systems that can be coupled with SWRO and could compete with the current state of the art RE technologies sustainably seeing as the main issue with existing technologies is intermittency. Accordingly, AD has been considered as an alternative to fossil fuels for electricity generation and was compared to the most commonly applied technologies: PV and wind. Additionally, no study has considered the design of a RE plant specific to the SWRO requirements, but rather consider existing plants in the studied regions. Accordingly, this study employs three different software to design each of RE plants to satisfy the energy requirements of the SWRO plant and perform the LCA, taking into account the impact of land use which has not been previously accounted for. In regard to spatial context, no Lebanese case study has been addressed prior to this work.

CHAPTER 3

METHODOLOGY

The aim of this research is to perform an LCA on a SWRO plant powered by the Lebanese electricity grid versus 3 forms of RE: PV, wind and biogas from AD. This section will describe the methodology followed and the software used in the design of the different components. As seen in the flowchart in figure 3, the SWRO design was done using WAVE software, the RE plant components were completed using HOMER Pro and the LCA was done using Simapro PhD version 9 with the Ecoinvent databases. The subsequent parts of this section will detail the different designs that were adopted.

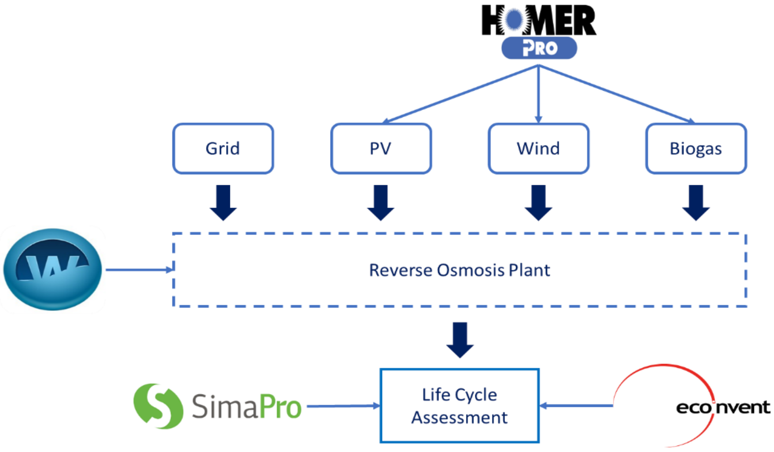

Figure 3 Methodology flowchart

3.1. Design of SWRO and RE systems

In this section, the methodology followed to design the SWRO plant and each of the RE systems: PV, wind and biogas will be detailed, followed by a description of the case study that was adopted in this project.

3.1.1. SWRO plant

The design of the SWRO plant was done using WAVE (Water Application Value Engine) software which was developed by Dow Water and Process Solutions as an update of the ROSA software program. This software includes calculation setups to design RO plants optimally and it incorporates the latest Dow RO products, such as DOW FILMTEC elements (Wave Software For Water Treatment Plant Design, 2019).

Reverse osmosis is the process by which dissolved solids are separated from water using a semi permeable membrane. To do so, a pressure higher than the osmotic pressure is exerted on the water to be treated (brackish or seawater) to retain the salts and allow water to flow across the membranes. A set of membranes is typically placed inside a pressure vessel which serves as a “housing” for the membranes. The resulting pure water stream is referred to as permeate and the concentrated salts stream is referred to as brine or concentrate. Recovery refers to the volume percent of pure water recovered from the feed. There are different flow patterns in which RO systems can be configured. In general, a stage refers to an arrangement whereby the combined reject from each pressure vessel in a first stage is fed to another set of pressure vessels in a second stage to increase recovery. As for a pass, it refers to further purification of the permeate by passing it into another RO. In any case, all RO systems require pretreatment of the source water to remove suspended solids and bacteria that are harmful to RO membranes.

The objective of the SWRO plant design is to satisfy the freshwater needs of the chosen town with as minimal energy consumption as possible. To do so, some parameters like permeate flow rate (calculated based on water demand), feed water quality, design temperature and type of pretreatment were fixed and input into WAVE. Other parameters were varied until an optimal configuration was reached and adopted. The variable parameters were number of stages, number of passes, number of pressure vessels, types of membranes and number of membranes per pressure vessel. The final decision was based on a compromise between maximum attainable recovery, minimum specific electricity consumption, minimum number of membranes and minimum feed pressure. The flux and final water quality (TDS, ion concentration and pH) also needed to be within required limits and variables were adjusted accordingly.

As for the pretreatment, a conventional pretreatment was chosen and designed based on the guidelines given in Voutchkov (2013). Usually, the unit processes to be included in the pretreatment are determined based on the source water quality. However, for this study, since no information was available regarding the physical characteristics of the seawater in the chosen region, the most typical pre-treatment units in RO systems were adopted and sized. For all the units, the design flow rate was increased by 5% than the one entering the RO to account for backwashing the filters. For the multimedia, activated carbon, cartridge filters and cartridge filter housings, initial calculations were done based on a chosen filtration rate (depending on guidelines) to determine the required filtration areas. Existing filters from manufacturers were selected such that their construction materials comply with the source water quality and they can sustain a certain flow rate according to which the number of required filters was calculated. The backwash pump flow rate was decided based on a standard rise rate and the individual filter area. The pre and post treatment chemical specifications were extracted from the WAVE chemical library and the dosage capacities were calculated accordingly. The actual dosage pumps were oversized by 50%. The chemical storage tanks were designed to allow for 24-hour storage of chemicals. All the pumps required in the process were selected from the Grundfos website (www.grundfos.com) based on the flow rate and head. As for the pressure exchanger, a design given by ERI (www.energyrecovery.com) was selected. The clean-in-place was designed based on the membrane area of the RO and it involved 6 cleaning steps as recommended in Voutchkov (2013). The seawater intake and discharge are very site specific and since no information was available regarding the available source water, general calculations were done and the construction materials were chosen based on the Mediterranean seawater. The outfall design accounted for the concentrate, backwash water and membrane flush water, and it was designed with the help of a spreadsheet developed by Bleninger *et al.* (2009).

3.1.2. RO plant description

3.2. Renewable energy

Three forms of renewable energy were considered and were designed using HOMER Pro (Hybrid Optimization of Multiple Energy Resources) software which combines traditionally generated and renewable power to simulate integrated microgrid systems by applying an optimization model. Several scenarios were designed in order to meet the power requirements of the SWRO plant. This section will describe the methodology followed to complete the designs.

3.2.1. PV

Solar photovoltaic refers to the conversion of sunlight into electricity using semi-conductors. This is done using PV panels made of PV cells in which the semi-conductors are embedded. When the sun hits the semi-conductors, electrons are freed forming an electric DC current. However, because almost all appliances operate on AC power, an inverter is employed to transform the current from DC to AC. Different types of semiconductor materials exist among which the current most commonly used one is Silicon, which in its turn can have several forms with varying efficiencies.

Lebanon has over 300 days of sunshine per year amounting to an average of 2.8-8.42 kWh/m^2.day. The solar data for Lebanon was taken from the report “Renewable energy and industry” by UNDP-CEDRO and is shown in figure 4.

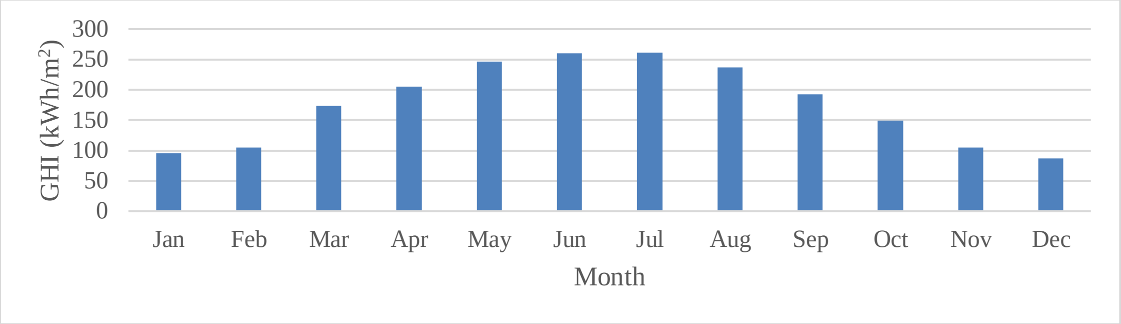

Figure 4 Lebanon solar data

Off-grid and on-grid PV systems with different renewable percentages were investigated. To do so, the plant electric load and the solar resource provided above were input into HOMER, along with the components required for the PV plant which are inverter, solar panels and either grid or batteries. Iterations involved varying the capacity of each of these components and for off-grid scenarios, different battery capacities were tested. Decisions were based on plants with minimal capacity (i.e. minimal number of panels), minimal cost of energy and minimal number of batteries.

The same PV panel was used for all scenarios. The chosen panel is a 360-Watt mono-crystalline module from SunPower (X22-360-D-AC). It has an area of 1.63 m^2 and its dimensions are shown in figure 5. The panel datasheet is accessible through the SUNPOWER website.

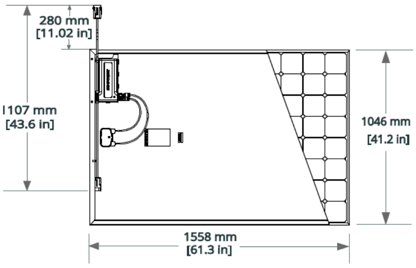

Figure 5 PV panel specifications

The types of batteries that were used and their specifications are summarized in table 4.

Table 4 Battery types and specifications

Battery specifications					
Type	**Rated energy**	**Length (mm)**	**Width (mm)**	**Height (mm)**	**Weight (kg)**
Tesla Powerwall 2.0	13.5 kWh	753	147	1150	114
EnerDel Secure+	101 kWh	1731	786	2373	2245
Intensium Max +20M	1.1 MWh	6058	2438	2896	19500

3.2.2. Wind

Wind energy is the process by which wind is used to generate electricity. Wind turbines are typically made of three blades that rotate when wind blows over them, causing a rotor to spin and the shaft of a generator to also rotate producing electricity. The components of the turbine are generally housed by what is referred to as nacelle, which sits on top of a tower supporting the structure of the turbine.

The wind resource for Akkar was taken from World Weather Online historical data as average wind speeds for the year 2018 shown in figure 6.

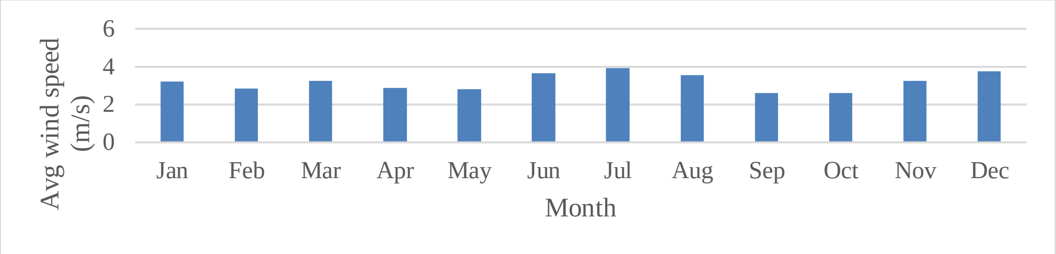

Figure 6 Lebanon wind data

Off-grid and on-grid wind systems with different renewable percentages were designed in HOMER. The plant electric load, the wind speed, and temperature were input, along with the components required for the wind plant which are wind turbines of different capacities and either grid or batteries (with inverter). Iterations involved varying the capacity of each of these components. For off-grid scenarios, different battery capacities were tested. Decisions were based on plants with minimal capacity (i.e. minimal number of turbines), minimal cost of energy and minimal number of batteries. For off-grid systems, the same battery capacities that were used for PV were tested (table 4). Turbines with increasing capacities whose specifications are found in table 5 were used in order to observe the impact of different turbine capacities.

Table 5 Wind turbine specifications

Name	**Rated capacity**	**Rotor diameter**	**Tower height**	**Reference**
Nordex N50	800 kW	50 m	46/50/70 m	wind-turbine-models.com, 2019
Enercon E-82	2 MW	82 m	78 m	ENERCON product overview, 2015
Enercon E-126 EP4	4.2 MW	127 m	132 m	ENERCON product overview, 2015

3.2.3. Biogas

Anaerobic digestion is a biological process by which biodegradable materials are broken down in the absence of oxygen resulting in biogas which is burned in a generator to produce electricity. The main components of this process are the generator and the digester which is a tank that can have different commercially available variations.

For this project, due to the absence of reliable data as no AD plant exists in Lebanon except in Saida, the amount of waste was estimated based on the data in table 6 taken from the Country Report on Solid Waste Management in Lebanon by Sweepnet (2014). The calculations of estimated waste generated in 2019 are shown in table 7 where the per capita waste was calculated based on the MSW generation rate in 2013 and the MSW generation yearly growth. The waste per town is the per capita value multiplied by the town population (30,000). As for the biowaste, it was considered as the organic fraction of the waste being 52.5% in 2013 (similar value was assumed for 2019).

Table 6 Waste generation data

Year	2013
MSW generation in rural areas	0.85 kg/capita.day
MSW generation growth	1.65 % per year
Organic waste fraction	52.50%

Table 7 Biomass resource calculation

Year	**Waste per capita (kg/p/d)**	**Waste per town (kg/d)**	**Biowaste (kg/d)**	**Biowaste (ton/d)**
2013	0.85	25500	13388	13.39
2014	0.86	25921	13608	13.61
2015	0.88	26348	13833	13.83
2016	0.89	26783	14061	14.06

2017	0.91	27225	14293	14.29
2018	0.92	27674	14529	14.53
2019	0.94	28131	14769	**14.77**

The AD plant is approximated based on a plant in Zurich, Switzerland by KOMPOGAS and its specifications are summarized in table 8. The biogas is burned in a generator to produce electricity. The characteristics of the biogas are summarized in table 9 and were taken through communication with IBC plant in Saida. For data that were not given by IBC, values were approximated from the KOMPOGAS plant.

Table 8 AD unit characteristics

Capacity	5,400 tons/yr
Lifetime	20 years
Technology	Thermophile, single stage digestion with post composting
Temperature	55°C
Retention time	14 days

Table 9 Biogas characteristics

Gasification ratio	0.1 Nm^3/kg biowaste
Density	1.12 kg/m^3
Carbon content	16.23%
Lower heating value	6.2 MJ/kg dry matter

3.3. Life cycle assessment

The LCA was done using Simapro by PRé Sustainability. It is an LCA software that allows to model, analyze and compare environmental impacts of products and services in a systematic way. It helps identify hotspots in complex life cycles and incorporates different databases and LCIA methods and is structured according to the LCA steps given in ISO14040 series. The version used in this project is Simapro PhD 9.0.0.29. This section will describe the LCA steps applied.

3.3.1. Goal and scope

i. Goal

a. Reasons for carrying out the study

- Estimate the environmental load of producing water in a SWRO in Lebanon

- Compare the environmental impact of supplying the plant with different energy sources: Lebanese electricity grid, PV, wind, biogas.

b. Intended audience

- Any entity interested in understanding the environmental impact reductions that can be obtained when using RE to power SWRO plants.
- Governments, more specifically the ministry of the environment and water authorities, as well as water treatment companies interested in executing environmentally friendly water purification projects.

ii. Scope

a. Description of the product system

The studied system is a 4500 m^3/day SWRO plant whose design will be described in subsequent sections.

b. Function of the product system

The function of the product is to provide freshwater of adequate quality for domestic use, for a population of 30,000 people.

c. Functional unit

The functional unit is 1 m^3 of desalinated water and the SWRO plant is assumed to have a useful lifetime of 20 years, operating 345 days per year, 24 hours per day.

d. System boundaries

The system boundaries considered are shown in figure 7.

- Construction: involves all construction materials to build the plant components, their transformation processes, transportation to the plant site, and civil works.
- Operation: includes the chemicals used for pre and post treatment, cleaning solutions and electricity consumption of the process itself.

- Decommissioning: includes dismantling of structures at the end of the plant's useful life, transportation of the waste to treatment sites and the treatment operations.

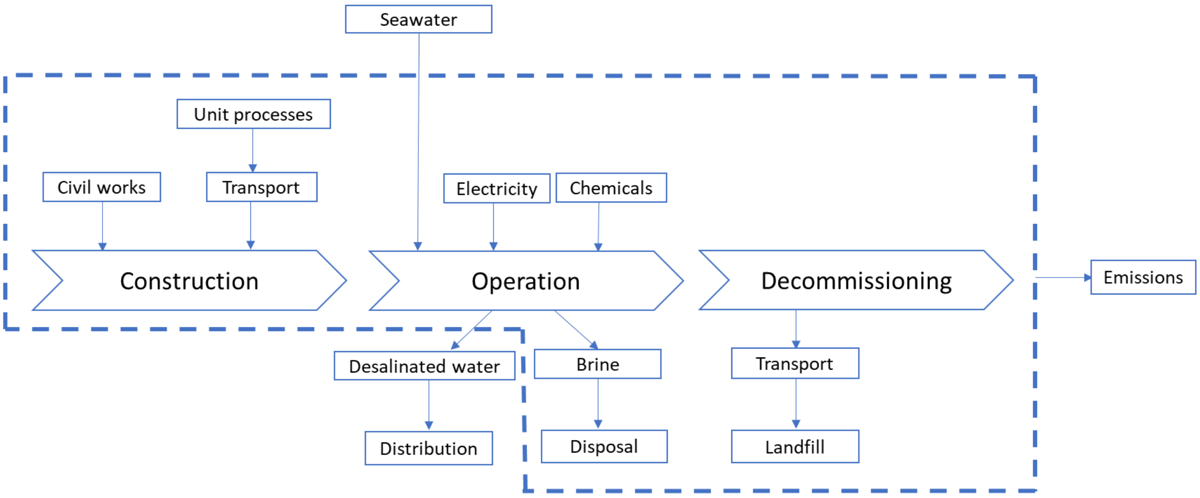

Figure 7 System boundaries

e. Source of data

Data for the SWRO plant was collected from literature, equipment manuals, and communication with industry and suppliers. Some values were calculated, assumed or estimated. Most processes used were from the Ecoinvent database. Data for the RE plants was extrapolated from existing plants.

3.3.3. Life cycle inventory

The system was divided into the three stages described above to facilitate analysis. Construction and dismantling were modeled as product stages, where construction was further divided into unit processes and operation was modeled as a transformation process. Construction of units mainly involved the materials used for construction; some units included material transformation processes, where sufficient data was found. The detailed inputs for all units can be found in Appendix E.

3.3.4. Life cycle impact assessment

The LCIA method used is IMPACT 2002+ tackling 14 midpoint categories: human toxicity (carcinogens + non carcinogens), respiratory inorganics, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/eutrophication, aquatic acidification, aquatic eutrophication, land occupation, global warming, non-renewable energy and mineral extraction, and 4 endpoint categories: human health, ecosystem quality, climate change and resources.

3.4. Case study

This section will describe the case study that was adopted in this project and the different scenarios that were considered.

3.4.1. RO plant

i. Plant capacity and location

The designed plant is a SWRO providing freshwater for a town with a population of 30,000, located in Akkar, North Lebanon. This district was chosen because many of its towns suffer from the detrimental effects of water shortage and it is located adjacent to the coast of the Mediterranean Sea. A water demand of 150 L/capita.day was assumed (10% safety margin from the value published by Chenoweth (2008)). Plant capacity is then calculated using the following equation.

$$Plant\ capacity = Per\ capita\ demand\ \times population = 150 \frac{L}{capita.day} \times 30{,}000 = 4{,}500{,}000\ L/day = \ 4{,}500\ m^3/day$$

ii. Feedwater quality

The feedwater is standard reference seawater with a Total Dissolved Solids of 35,000 mg/L, available in WAVE library. Its composition is very similar to that of the Mediterranean Sea and it can be found in Appendix B.

3.4.2. RE scenarios

Table 10 summarizes all the scenarios that were investigated. These include 100% Lebanese grid electricity and different percentages of each of solar PV, wind and biogas. Detailed descriptions of the scenarios will be provided in chapter IV.

Table 10 Description of scenarios

PV scenarios	**Description**	**Wind scenarios**	**Description**	**AD Scenarios**	**Description**
S1	100% grid	S1	100% grid	S1	100% grid
S2.1	10% PV, 90% grid	S3.1	10% wind, 90% grid	S4.1	10% AD, 90% grid
S2.2	20% PV, 80% grid	S3.2	20% wind, 80% grid	S4.2	20% AD, 80% grid
S2.3	30% PV, 70% grid	S3.3	30% wind, 70% grid	S4.3	30% AD, 70% grid
S2.4	40% PV, 60% grid	S3.4	40% wind, 60% grid	S4.4	40% AD 60% grid
S2.5	48% PV, 52% grid	S3.5	50% wind, 50% grid	S4.5	48% AD, 52% grid
S2.6.1	100% PV,13.5 kWh batteries	S3.6	60% wind, 40% grid		
S2.6.2	100% PV, 101 kWh batteries	S3.7	70% wind, 30% grid		
S2.6.3	100% PV, 1 MWh batteries	S3.8.1	100% wind,13.5 kWh batteries		
		S3.8.2	100% wind, 101 kWh batteries		
		S3.8.3	100% wind, 1 MWh batteries		

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents the main designs that were adopted for the SWRO plant and each of the RE systems, as well as the LCA results for the tested scenarios i.e. impact assessment and interpretation. The discussion involves the identification of hot spots and optimal scenarios and comparison of results to previous studies.

4.1. Design results

This section includes the design results obtained for the SWRO plant and scenarios for each of the RE systems.

4.1.1. SWRO plant

i. Configuration

The design that was adopted in this project is a single pass, 2-stage plant whose configuration is shown in figure 8. The membranes are 8-inch spiral-wound elements with 40.9 m^2 of active area, amounting to a total membrane area of 9402 m^2. The detailed report for the RO system by WAVE is found in Appendix C. Membrane datasheets can be found on the Dow website: https://www.dupont.com/water/reverse-osmosis.html#.

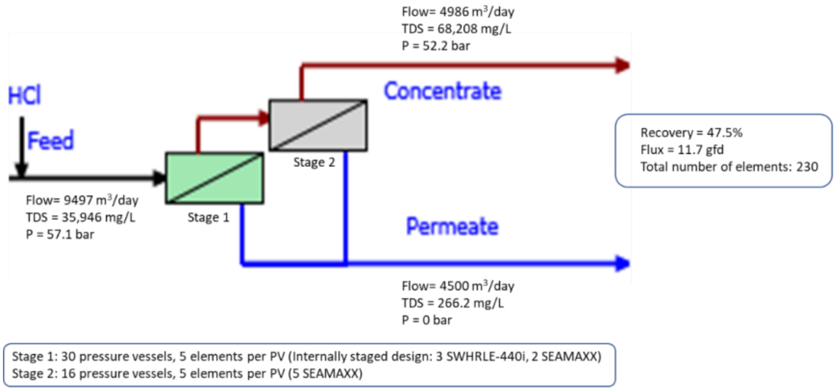

Figure 8 RO configuration

ii. Pretreatment and post treatment

The unit processes for the plant are shown in figure 9 and the design parameters are summarized in table 11. Calculations for units sizing are found in Appendix D.

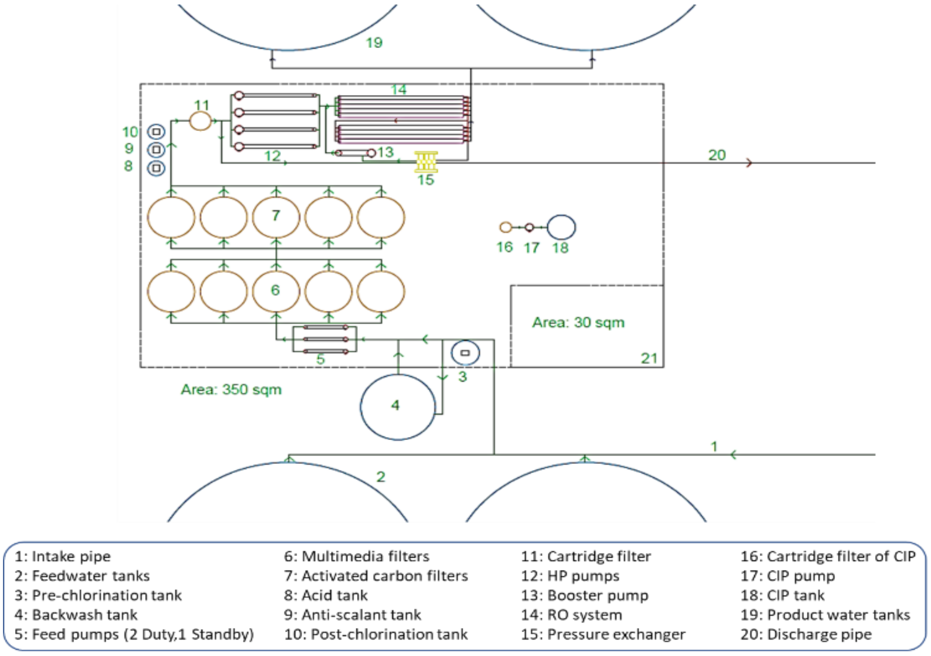

Figure 9 SWRO plant layout

Table 11 Unit processes description

Component	**Purpose**	**Design parameters**
Seawater intake	Supply of seawater into pretreatment system	Intake type: offshore velocity cap Flow rate: 9972 m^3/day Distance from shore: 400 m Material: HDPE and super duplex stainless steel
Feedwater tanks	2-hour storage of feedwater per tank	Number of tanks: 2 Tank capacity: 887 m^3 Tank diameter: 12.7 m, tank height: 7 m
Pre-chlorination	Disinfection and microbe removal	Chemical used: Sodium hypochlorite Dosage: 2 ppm Tank capacity: 500 L Tank material: HDPE Dosing pump flow rate: 5.8 L/hr
Feed pump	Pump feedwater across pre-treatment	Number of pumps: 2 duty, 1 standby Pump flow rate: 210 m^3/hr Pump head: 3 bars
Multimedia filters	Removal of suspended solids and turbidity	Number of filter vessels: 5 Vessel material: stainless steel Vessel capacity: 2.72 m^3 of media Vessel diameter: 2.1336 m Vessel height: 1.524 m Gravel: 0.05m, Silica sand: 0.24 m, anthracite: 0.2 m
Activated carbon filters	Removal of organics and chlorine to prevent membrane damage	Number of filter vessels: 5 Vessel material: stainless steel Vessel capacity: 2.72 m^3 of media

		Vessel diameter: 2.1336 m Vessel height: 1.524 m Activated carbon: 0.76 m
Backwash	Cleaning of media and activated carbon filters after a certain pressure drop	Tank capacity: 30 m^3 Pump flow rate: 89 m^3/hr Pump head: 5 bars Number of pumps: 3 Backwash duration: 20 mins Source water: permeate
Acid addition	Reduction of calcium carbonate, calcium phosphate or calcium fluoride scaling potential and pH adjustment	Chemical used: Hydrochloric acid Dosage: 40.6 ppm Tank capacity: 500 L Tank material: HDPE Dosing pump flow rate: 14.3 L/hr
Anti-scalant addition	Reduction of membrane scaling potential	Chemical used: Sodium hexametaphosphate Dosage: 3 ppm Tank capacity: 500 L Tank material: HDPE Dosing pump flow rate: 0.5 L/hr
Cartridge filter	Further filtration of residual sand and solids	Number of cartridges: 120 Cartridge length: 1016 mm Filter size: 5 µm Filter material: polypropylene Number of vessels: 4 (36 cartridges per vessel) Vessel material: stainless steel
HP pump	Pumping pre-treated water across RO membranes at a high pressure	Pump flow rate: 190 m^3/hr Pump head: 55.1 bar Number of pumps: 4
Booster pump	Increase pressure of water into RO	Pump flow rate: 210 m^3/hr Pump head: 2.52 bar Number of pumps: 4
Pressure exchanger	Transfer energy from high-pressure concentrate stream to low pressure feed stream (energy recovery device)	Number of PX: 4 Flow rate per PX: 52.9 m^3/hr
Clean-in-place	Frequent cleaning of RO membranes	CIP tank capacity: 2500 L CIP tank material: HDPE CIP pump flow rate: 48 m^3/hr Pump head: 4.5 bar Number of pressure vessels cleaned: 6 Cartridge filter: PP 1016 mm, 13 cartridges,1 SS vessel
Post-chlorination	Final disinfection	Chemical used: Sodium hypochlorite Dosage: 1 ppm Tank capacity: 500 L Tank material: HDPE Dosing pump flow rate: 1.38 L/hr
Product water tanks	5-hour storage of feedwater per tank	Number of tanks: 2 Tank capacity: 887 m^3 Tank diameter: 12.7 m, tank height: 7 m
Outfall	Discharge of brine and other waste into ocean	Flow rate: 6613 m^3/day Discharge TDS: 53942 ppm Port height: 0.5 m Distance from shore: 440 m Material: HDPE

Overall, the plant has an electricity consumption of 3 kWh/m^3; detailed calculations can be found in appendix E1.

4.1.2. RE plants

This section describes in detail the scenarios that were selected for each form of RE. For all systems, since the plant consumes 3 kWh/m^3 of electricity, the electric load was calculated as follows assuming 24 hours of operation daily. The same load was assumed for all months of the year.

$$Electric\ load = 3\frac{kWh}{m^3} \times 4500\frac{m^3}{day} \times \frac{day}{24\ hours} = 562.5\ kW$$

i. <u>PV scenarios</u>

The scenarios simulated for PV are summarized in tables 12 and 13. For on-grid systems, the maximum attainable renewable percent was 48% due to the limited availability of the solar resource (e.g. in winter months or at night).

Table 12 PV on-grid simulations

PV, on grid													
Installed capacity (kW)	**PV (kWh/yr)**	**Grid (kWh/yr)**	**Total cons (kWh/yr)**	**Excess (kWh/yr)**	**Losses (kWh/yr)**	**% PV**	**% grid**	**Inverter (kW)**	**Operating cost ($/kWh)**	**# of panels**	**Area (m^2)**	**Grid Sales (kWh/yr)**	**Total production (kWh/yr)**
300	485,424	4,442,076	4,927,500	**-**	25,550	**9.85%**	90.15%	290	0.1067	833	1358	33	511,007
600	950,805	3,976,695	4,927,500	6,889	50,757	**19.30%**	80.70%	483	0.1129	1667	2716	13,564	1,022,015
1100	1,464,014	3,463,486	4,927,500	9,312	93,219	**29.71%**	70.29%	900	0.1224	3056	4980	307,149	1,873,694
3100	1,980,894	2,946,606	4,927,500	**-**	264,021	**40.20%**	59.80%	3094	0.1434	8611	14033	3,035,495	5,280,410
13000	2,361,800	2,565,700	4,927,500	11,247,864	544,790	**47.93%**	52.07%	3094	0.271	36111	58849	7,989,203	22,143,657

Table 13 PV-off grid simulations

PV, off grid													
Installed capacity (kW)	**Battery**	**Number of batteries**	**PV (kWh/yr)**	**Total cons (kWh/yr)**	**Excess (kWh/yr)**	**Losses (kWh/yr)**	**% PV**	**Inverter (kW)**	**Operating cost ($/kWh)**	**# of panels**	**Panel area (m^2)**	**Battery area (m^2)**	**Total production (kWh/yr)**
8,860	13.5 kWh	2,915	4,927,500	4,927,500	9,618,993	544,570	100%	3,094	0.9794	24,611	40,108	323	15,091,062
7,172	101 kWh	669	4,927,500	4,927,500	6,905,762	383,313	100%	3,094	0.9683	19,922	32,467	910	12,216,574
10,125	1 MWh	44	4,927,500	4,927,500	11,774,996	544,432	100%	3,094	1.26	28,125	45,834	650	17,246,928

ii. Wind scenarios

The scenarios simulated for wind are summarized in tables 14 and 15. For on-grid systems, the maximum attainable renewable percent was 70% due to the limited availability of the wind resource (e.g. in summer months).

Table 14 Wind on-grid simulations

Wind, on grid										
Installed capacity (MW)	**Turbine capacity (MW)**	**Number of turbines**	**Wind (kWh/yr)**	**Grid (kWh/yr)**	**Total cons (kWh/yr)**	**% wind**	**% grid**	**Operating cost ($/kWh)**	**Grid Sales (kWh/yr)**	**Total production (kWh/yr)**
0.8	0.8	1	543,411	4,384,089	4,927,500	**11.03%**	88.97%	0.112	12,823	556,234
1.6		2	967,600	3,959,900	4,927,500	**19.64%**	80.36%	0.1238	144,868	1,112,468
2	2	1	1,387,729	3,539,771	4,927,500	**28.16%**	71.84%	0.1096	421,402	1,809,131
4		2	2,042,441	2,885,059	4,927,500	**41.45%**	58.55%	0.1157	1,575,820	3,618,261
6		3	2,426,298	2,501,202	4,927,500	**49.24%**	50.76%	0.1194	3,001,094	5,427,392
8.4	4.2	2	2,935,496	1,992,004	4,927,500	**59.57%**	40.43%	0.08741	6,201,047	9,136,543
16.8		4	3,416,743	1,510,757	4,927,500	**69.34%**	30.66%	0.08584	14,856,343	18,273,086

Table 15 Wind off-grid simulations

Wind, off grid												
Installed capacity (MW)	**Turbine capacity (MW)**	**Number of turbines**	**Battery**	**Number of batteries**	**Wind (kWh/yr)**	**Total cons (kWh/yr)**	**Excess (kWh/yr)**	**Losses (kWh/yr)**	**% Wind**	**Inverter (kW)**	**Operating cost ($/kWh)**	**Total production (kWh/yr)**
21	4.2	5	13.5 kWh	2,937	4,927,500	4,927,500	17,498,243	415,615	100%	2,290	1.17	22,841,358
17	4.2	4	101 kWh	597	4,927,500	4,927,500	12,996,461	349,127	100%	2,724	0.9882	18,273,087
25	4.2	6	1 MWh	43	4,927,500	4,927,500	22,093,081	389,050	100%	2,925	1.49	27,409,630

iii. Biogas scenarios

The scenarios simulated for biogas are summarized in table 16. The maximum attainable renewable percent was 48% due to limited amount of waste transformed.

Table 16 Biogas on-grid simulations

Biogas												
Generator capacity (kW)	**Biogas (kWh/yr)**	**Grid (kWh/yr)**	**Total cons (kWh/yr)**	**% biogas**	**% grid**	**Operating cost ($/kWh)**	**Avg fuel cons (ton/day)**	**Total fuel cons (ton/yr)**	**Specific fuel cons (kg/kWh)**	**Fuel energy input (kWh/yr)**	**Grid sales (kWh/yr)**	**Total production (kWh/yr)**
60	525,567	4,401,933	4,927,500	**10.67%**	89.33%	0.09626	3.32	1211	0.258	234,000	33	525,600
110	963,514	3,963,986	4,927,500	**19.55%**	80.45%	0.09313	6.08	2220	0.258	428,000	86	963,600
170	1,488,858	3,438,642	4,927,500	**30.22%**	69.78%	0.08939	9.4	3430	0.258	662,000	172	1,489,030
225	1,969,964	2,957,536	4,927,500	**39.98%**	60.02%	0.08595	12.4	4540	0.258	876,000	811	1,970,775
270	2,361,941	2,565,559	4,927,500	**47.93%**	52.07%	0.08313	14.9	5448	0.258	1,050,000	2989	2,364,930

4.2. LCA results for individual RE-SWRO combinations

4.2.1. PV results

a. Global warming

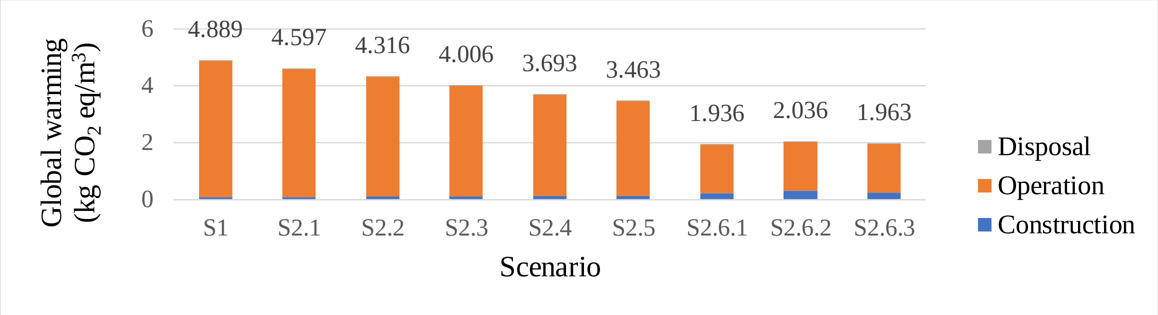

Figure 10 Global warming PV

In S1, global warming amounts to 4.889 kg CO_2 eq/m^3 of which 98% is due to the operation phase. Within operation, 64% is attributed to electricity consumption and 36% to chemicals. This figure decreases as the fraction of PV increases. For on-grid scenarios, a maximum reduction of about 30% reaching a value of 3.463 kg CO_2 eq/m^3 was achieved in S2.5, where operation phase accounts for 96%. However, in this case, within the operation phase, electricity consumption accounts for 50% and chemical use for the remaining 50%. For off-grid scenarios, a maximum reduction of 60% was achieved in S2.6.1. reaching a value of 1.936 kg CO_2 eq/m^3, operation phase accounting for 88%, which is purely due to chemical use and 0% due to electricity consumption, as no fossil fuels are consumed. For all PV scenarios, operation remains the highest contributor despite having a decreased impact compared to the baseline (S1) scenario. Despite having minimal impact, the impact from construction phase in S1 is mostly caused by membrane production (57%) followed by civil works (16%) and activated carbon (11%) and multimedia (8%) filters. As % PV increases, global warming caused by construction increases. However, impact from SWRO plant remains higher than that from PV plant except in off-grid scenarios and this distribution of impact is attributed to panel production, mounting system and battery production.

b. Mineral extraction

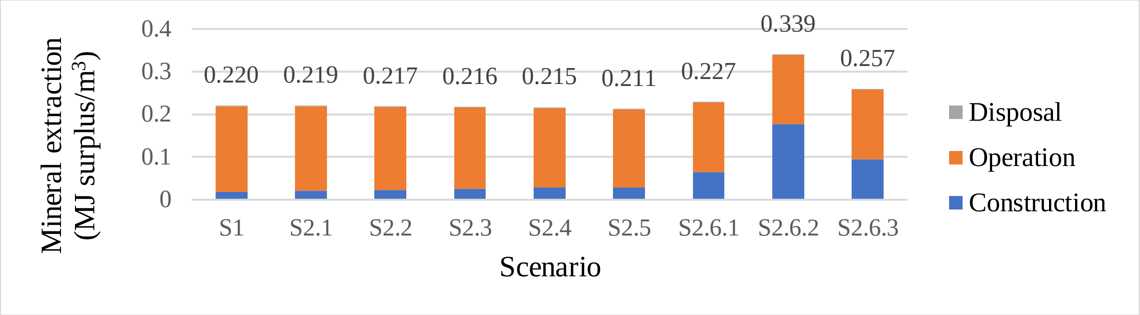

Figure 11 Mineral Extraction PV

Within on-grid scenarios, mineral extraction had the highest value in S1 with a value of 0.22 MJ/m^3 (92% operation, 8% construction) and the lowest impact in S2.5 with a value of 0.211 MJ/m^3 (86% operation, 14% construction), which is only a 4% reduction. The reason behind this is that within the operation phase, the main contributor is HCl consumption (74% and 81% for S1 and S2.5 respectively) and not electricity use, i.e. the use of RE will not have significant influence in reducing the impact in this category. The impact from construction increases with increase in % PV due to additional building requirements associated to PV panels and mounting system.

Within off-grid scenarios, an increase in mineral extraction is observed with respect to S1, with the maximum value in S2.6.2. of 0.339 MJ/m^2. Because for 100% PV, operation in all 3 scenarios contributes the same amount, the increase in mineral extraction is attributed to an increase in the construction phase, which is associated with the bigger panel area, mounting system and more importantly battery production whereby they account for 51%, 85% and 71% in S2.6.1, S2.6.2 and S2.6.3 respectively.

For the SWRO plant construction, activated carbon and multimedia filters followed by civil works are the main contributors to mineral extraction.

c. Non-renewable energy

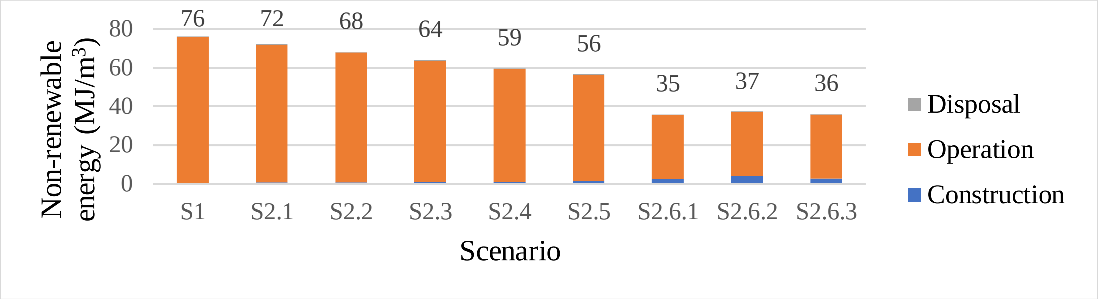

Figure 12 Non-renewable energy PV

Non-renewable energy refers to the total primary energy extracted (MJ primary) and is calculated based on upper heating values. The operation phase is the major contributor in this category for all scenarios, ranging from 99% of the total in S1 to 89% in S2.6.2. Non-renewable energy is 76 MJ/m^3 in S1 and decreases by a maximum of 26% to 56 MJ/m^3 in S2.5. A further decrease of about 38% is observed when moving to 100% PV in S2.6.1., which is a 53% reduction from S1. In S1, 56% of operation is due to electricity use and 40% from HCl. As % PV increases, the load shifts to 55% HCl, 40% electricity use (for S2.5) and to 91% HCl, 0% electricity use in S2.6.2. Impact from construction increases with increase in PV plant size such that contribution of SWRO is higher than that of PV plant until S2.5 and scenarios that follow. Within SWRO construction, activated carbon filters and civil works are the highest contributors and to a lesser extent multimedia filters and membrane production.

d. Ecotoxicity (aquatic and terrestrial)

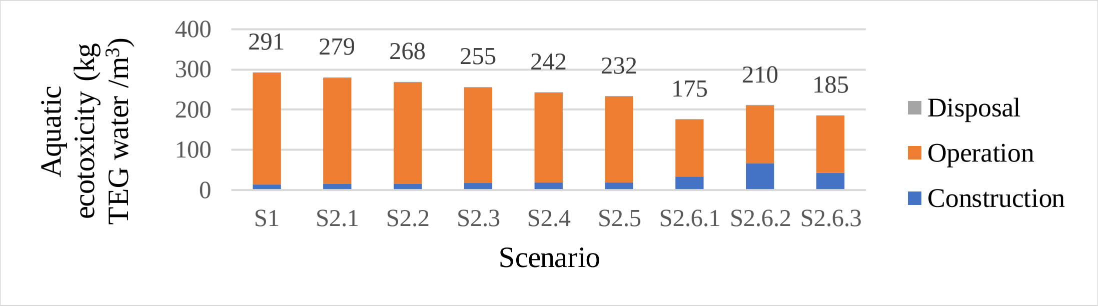

Figure 13 Aquatic ecotoxicity PV

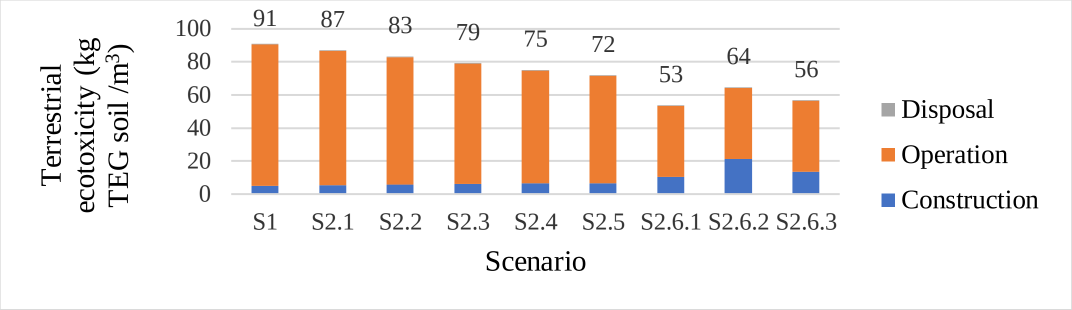

Figure 14 Terrestrial ecotoxicity PV

Aquatic and terrestrial ecotoxicity are measured by kg triethylene glycol into water and soil respectively. The maximum reduction achieved for both categories was 20% for on-grid scenarios, in S2.5, where terrestrial ecotoxicity decreased from 91 kg TEG soil/m^3 (S1) to 72 kg TEG soil/m^3 (S2.5) and aquatic ecotoxicity decreased from 291 kg TEG water/m^3 (S1) to 232 kg TEG water/m^3 (S2.5). As for off-grid scenarios, the maximum reduction that could be achieved was 40% from the baseline scenario, both in S2.6.1, to 53 kg TEG soil /m^3 and 175 kg TEG water/m^3 for terrestrial and aquatic ecotoxicity respectively. The operation phase in S1 is broken down into 50% electricity and 50% chemicals. As % PV increases, the breakdown shifts to 34% electricity and 66% chemicals in S2.5 and to 100% chemicals in all off-grid scenarios. Despite having the bigger portion of the impact from operation, the impact due to construction increases with the plant capacity due to increase in plant area, i.e. panel and mounting system area, reaching maximum values of 67 kg TEG water/plant and 21 kg TEG soil /plant in S2.6.2. SWRO contributes more than PV plants in all on-grid scenarios; however, the opposite is true for off-grid scenarios due to battery production. Within SWRO, tanks contribute the most, followed by activated carbon and multimedia filters and then civil works. As for PV plants, panels and mounting system are the highest contributors for on-grid scenarios and battery production for off-grid.

e. Human toxicity (carcinogens and non-carcinogens)

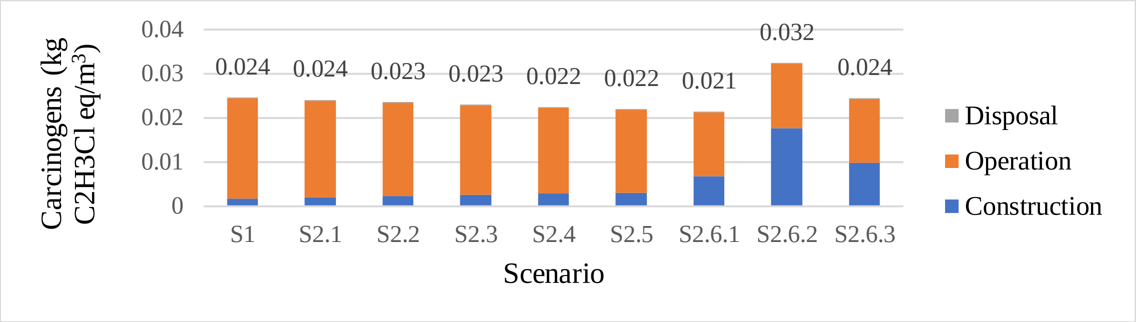

Figure 15 Carcinogens PV

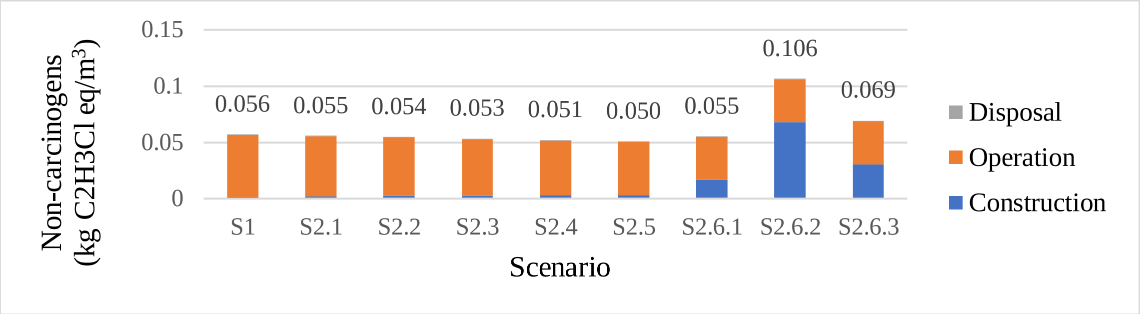

Figure 16 Non-carcinogens PV

Carcinogens and non-carcinogens reflect the human toxicity impacts of chemicals and are expressed in kg chloroethylene equivalents emitted into air. The reduction in both categories for on-grid scenarios compared to S1 is not significant (maximum of 11%); this is attributed to the fact that within the operation phase, the bigger proportion of impact corresponds to HCl and not electricity use. For off-grid scenarios, carcinogens decreased by 13% in S2.6.1, remained unchanged in S2.6.3 and increased by 32% in S2.6.2. Within operation, there is an equivalent decrease in impact for all 3 scenarios compared to S1 (from 0.023 kg C2H3Cl eq/m^3 in S1 to 0.0145 kg C2H3Cl eq/m^3 in S2.6.1., S2.6.2 and S2.6.3). The difference lies in construction where an increase is observed for 100% PV scenarios. Within construction, the increase in impact is not only proportional to panel area, but also to amount of batteries. This explains the fact that despite having the smallest area, S2.6.2 (33,000 m^2) displays the highest number of carcinogens compared to S2.6.1 (40,000 m^2) and S2.6.3 (46,000 m^2)

because of the higher weight of batteries. Batteries account for 47%, 83% and 66% of the carcinogens in the construction phase for S2.6.1, S2.6.2 and S2.6.3 respectively.

Non-carcinogens, in off-grid scenarios, decrease by 3% in S2.6.1 compared to S1, but increase by 88% and 22% in S2.6.2 and S2.6.3 respectively. Similar to carcinogens, there is an equivalent decrease in impact from operation in all 3 scenarios compared to S1 (from 0.055 kg C2H3Cl eq/m^3 in S1 to 0.038 kg C2H3Cl eq/m^3 in S2.6.1., S2.6.2 and S2.6.3). Accordingly, construction is responsible for the sizeable increase in non-carcinogens whereby batteries account for 73%, 94% and 86% in S2.6.1, S2.6.2 and S2.6.3 respectively. In all scenarios, SWRO construction contributes more that the PV plant until S2.4. for carcinogens and S2.6.1. for non-carcinogens. Within SWRO, civil works, activated carbon and multimedia filters are the highest contributors and to a lesser extent the intake pipe construction.

f. Air impacts (organics, inorganics, ionizing radiation, ozone depletion)

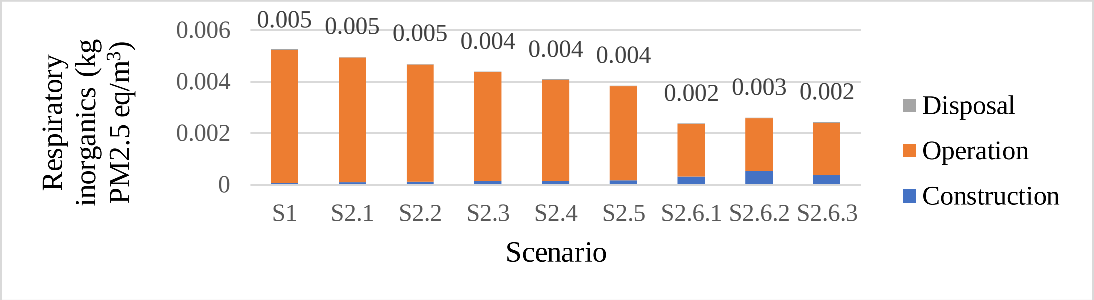

Figure 17 Respiratory inorganics PV

Respiratory effects caused by inorganics are measured by the amount of particulate matter emitted into air i.e. kg $PM_{2.5}$ eq. Respiratory inorganics amounted to 0.005 kg $PM_{2.5}$ eq/m^3 in S1, of which 98% were from the operation phase. As % PV increases, respiratory inorganics remain at almost 0.005 kg $PM_{2.5}$ eq/m^3 for S2.1 and S2.2, but decrease to an approximate 0.004 kg $PM_{2.5}$ eq/m^3 in S2.3, S2.4 and S2.5 which denotes that the decrease is very minimal within this category for on-grid scenarios (maximum of 27%). Within off-grid scenarios, a maximum reduction of 55% was observed in S2.6.1 and S2.6.3 (0.002 kg $PM_{2.5}$ eq/m^3), despite the increase in impact from construction, whereby it accounted for an average of 15% in both scenarios. The decrease in operation is the same for all 3 off-grid scenarios; however, S2.6.2 displays higher loads due to increase in construction whose main components are 60% batteries, 28% panels, 11% mounting system. This is almost a 373% increase above the value of construction in S1 (S1: 8E-05; S2.6.2:0.00038 kg $PM_{2.5}$ eq/m^3).

For the SWRO plant, the load is distributed between activated carbon and multimedia filters and to a lesser extent civil works, intake and tanks. SWRO plant has a higher contribution than the PV plant until S2.5.

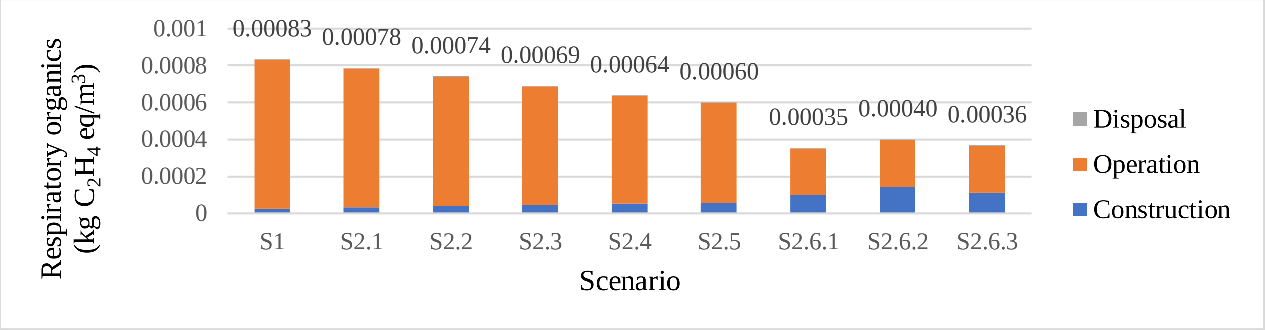

Figure 18 Respiratory organics PV

Respiratory organics refer to photochemical oxidation and are measured by kg ethylene into air. Only emissions of substances into air are considered in this category because it is unlikely that the considered pollutants will be emitted into soil or water. Typically, photochemical oxidation has impacts on human health in terms of respiratory effects and on ecosystem quality in terms of hindering plant growth. However, the latter is not currently taken into consideration because no studies support the calculation of the damage to ecosystem quality. Respiratory organics in S1 have a value of 0.00083 kg C_2H_4 eq/m^3 and were reduced by a maximum of 28% for on-grid scenarios, reaching a value of 0.0006 kg C_2H_4 eq/m^3 in S2.5. For off-grid scenarios, the impact was reduced by 58% to 0.00035 kg C_2H_4 eq/m^3 in S2.6.1. However, as % PV increases, there is an increase in load due to construction, going from an initial 2.5E-05 kg C_2H_4 eq/m^3 in S1 to 5.6E-05 kg C_2H_4 eq/m^3 in S2.5 and 0.000145 kg C_2H_4 eq/m^3 in S2.6.2. Within construction in S2.5 and S2.6.2, panels and mounting system have a higher impact in S2.5 than S2.6.2 due to the larger area, while batteries in S2.6.2 are responsible for the higher load. For the SWRO plant, the impact is mainly because of the membranes, tanks and civil works and to a lesser extent multimedia and activated carbon filters.

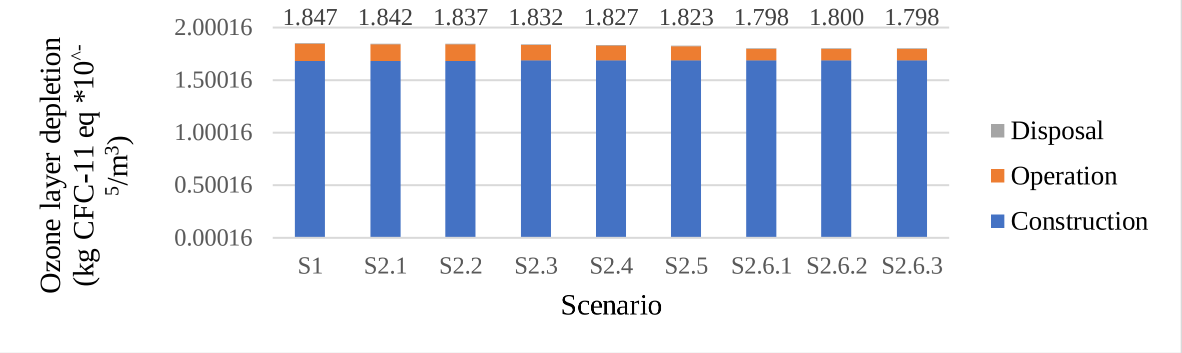

Figure 19 Ozone layer depletion PV

Ozone layer depletion is measured in kg CFC-11 eq into air only because the considered pollutants are unlikely to be emitted into soil or water. It ranges from 1.847E-05 kg CFC-11 eq/m^3 in S1 to 1.798E-05 kg CFC-11 eq/m^3 in S2.6.1 and S2.6.3. The reduction in this category is very minimal (maximum 3%). This is because in all scenarios, construction contributes about 91-94% of the load and within this phase, SWRO construction contributes 100% compared to the PV plant. Accordingly, increase in PV plant capacity and area cause very insignificant increases in ozone layer depletion. The main component within construction is the membrane production. Although minimal, the 3% reduction when moving from grid to PV is caused by the decrease in ozone layer depletion within the operation phase.

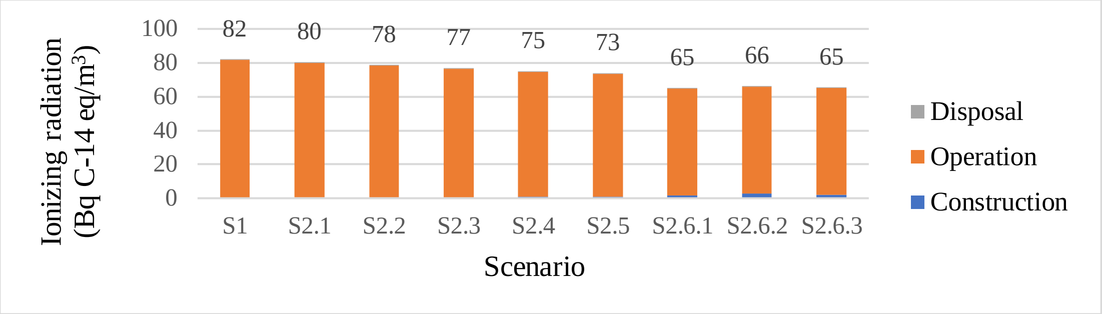

Figure 20 Ionizing radiation PV

Ionizing radiation is expressed in becquerel of carbon-14 equivalent into air and water. It has a value of 82 Bq C-14 eq/m^3 in S1. It decreases as % PV increases to a minimum of 73 Bq C-14 eq/m^3 in S2.5 (10% reduction) and 65 Bq C-14 eq/m^3 in S2.6.1 and S2.6.3 (20% reduction). Operation accounts for 100% of the impact in S1 and decreases to 97% in S2.6.1 and S2.6.3. The reason for this is that in S1 operation, 23% is from electricity and 77% chemicals and construction only slightly increases as % PV increases because of panel production. Batteries have an impact, but not as significant as panels. For SWRO, most of the impact is caused by activated carbon filters followed by multimedia filters and civil works, followed by membranes and intake.

g. Acidification and eutrophication (aquatic acidification, aquatic eutrophication, terrestrial acidification/nutrification)

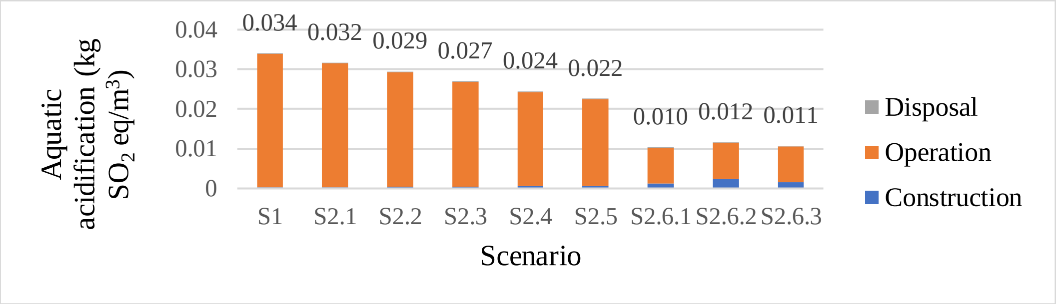

Figure 21 Aquatic acidification PV

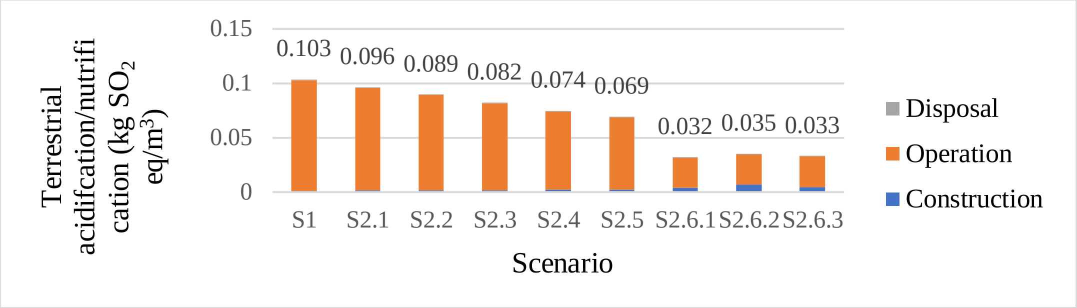

Figure 22 Terrestrial acidification/nutrification PV

Aquatic acidification and terrestrial acidification/nutrification can be interpreted using the same logic. Essentially, both are measured in kg SO_2 eq into air/m^3; however, the characterization factors for aquatic acidification are given for emissions into air, water or soil, while those for terrestrial acidification/nutrification are given for emissions into air only (Humbert, Schryver, Bengoa, Margni, & Jolliet, 2012). The major contributor in both categories for all scenarios is operation, accounting for almost 99% of the overall load in S1 and 80% in S2.6.2. For both categories, impact could be reduced by a maximum of 34% from the baseline scenario for on-grid scenarios and by 70% for off-grid scenarios (Aquatic acidification: S1: 0.034 kg SO_2 eq/m^3, S2.5: 0.022 kg SO_2 eq/m^3, S2.6.1: 0.01 kg SO_2 eq/m^3; Terrestrial acidification/nutrification: S1: 0.103 kg SO_2 eq/m^3, S2.5: 0.069 kg SO_2 eq/m^3, S2.6.1: 0.032 kg SO_2 eq/m^3). The reduction is notable in both categories; with increase of % PV, impact from operation decreases and that from construction increases. However, the increase in construction does not have measurable impact on the overall results because it is not as pronounced as the decrease in operation, which explains the net decrease in impact. Within operation, S1 has 73% of its impact due to electricity and the rest due to chemicals which explains the significant decrease in impact. The increase in construction is mostly due to panel production and batteries in off-grid scenarios (though not as pronounced as panels except in S2.6.2). For SWRO, terrestrial acidification/nutrification is caused by tanks and to a lesser extent civil works, activated carbon and multimedia filters. Aquatic acidification is caused equally by activated carbon filters, tanks and civil works and to a lesser extent multimedia filters.

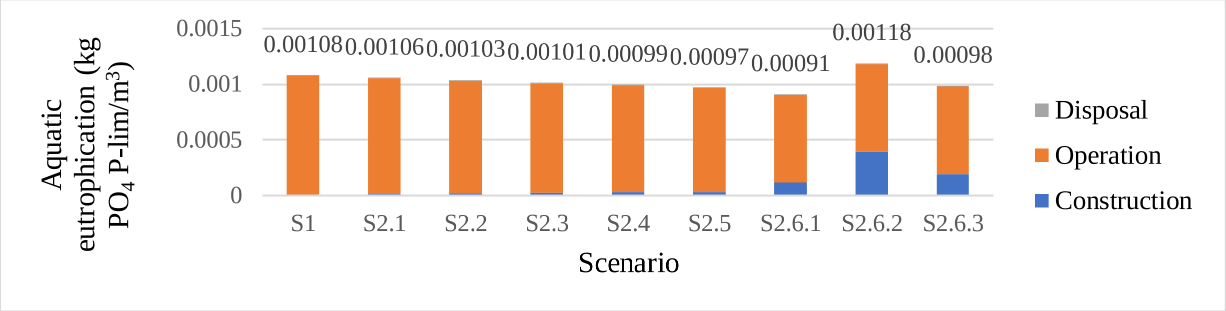

Figure 23 Aquatic eutrophication PV

Aquatic eutrophication is quantified by kg PO_4^{3-} into water/m^3. S1 has a value of 0.00108 kg PO_4^{3-}/m^3. The reduction for this category is not very notable for on-grid scenarios; a maximum of 10% was achieved in S2.5 reaching a value of 0.00097 kg PO_4^{3-}/m^3. For off-grid scenarios, S2.6.1 and S2.6.3 showed reductions of 16% and 9% respectively, while S2.6.2 displayed a 10% increase. The reason behind this is that the major impact in this category is due operation within which chemical use has a higher contribution than electricity use. As such, increasing PV plant capacity increases the impact from the construction phase due to larger panel area, mounting system and weight of batteries. In S2.6.2, the impact from construction increased by almost 4400% from that in S1, while the impact from operation decreased by 26%. For SWRO, impact is due to civil works, activated carbon and multimedia filters and control system.

h. Land occupation

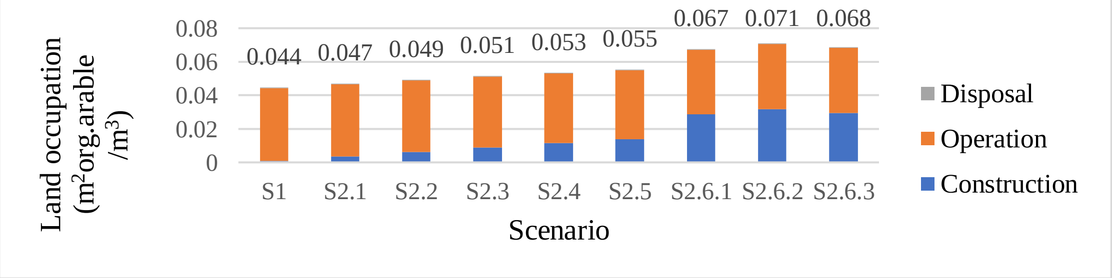

Figure 24 Land occupation PV

Land occupation is expressed in m^2 organic arable land-eq/m^3. This is the only category in which the impact increases for all scenarios compared to the baseline scenario. S1 has a value of 0.044 m^2 org arable land-eq/m^3, which increases to a maximum value of 0.055 m^2 org arable land-eq/m^3 in on-grid scenarios (24% increases) and 0.071 m^2 org arable land-eq/m^3 for off-grid scenarios (60% increase). Operation accounts for the higher portion of land occupation for all scenarios; however, as % PV increases operation decreases very minimally, and the portion of construction increases, causing a net increase in impact. Within operation, the high impact is due to chemicals and not electricity (74% HCl, 11% electricity for S1). Within construction, increase in area requirements increases impact due to panels and mounting system. Batteries have minimal impact on land occupation; the bigger proportion is due panels and mounting system (S2.6.1: 98%, S2.6.2: 89%, S2.6.3: 95%). For SWRO, land occupation is caused by civil works followed by membranes, activated carbon and multimedia filters.

4.2.2. Wind results

a. Global warming

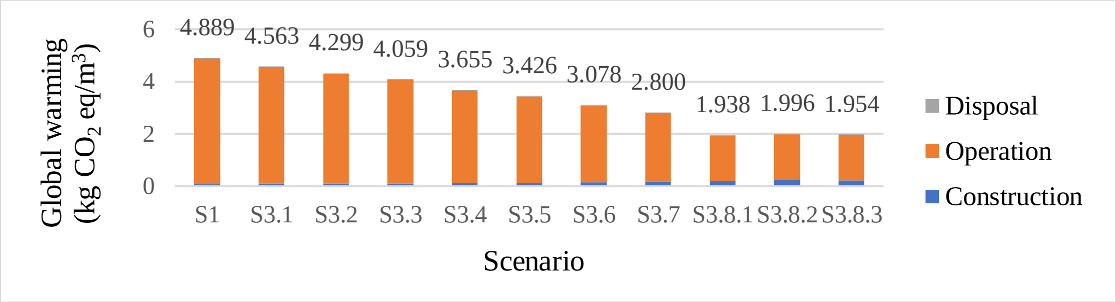

Figure 25 Global warming wind

For global warming, the baseline scenario has a value of 4.889 kg CO_2 eq/m^3. The maximum reduction that could be achieved was 43% for on-grid scenarios in S3.7 reaching a value of 2.8 kg CO_2 eq/m^3, and 60% for off-grid scenarios in S3.8.1 reaching a value of 1.938 kg CO_2 eq/m^3. In all scenarios, operation is the major contributor to global warming; within operation, the bigger portion of the impact shifts from electricity consumption to chemical use, whereby in S1, electricity use accounts for 64% of operation impact, while in S3.7, grid electricity accounts for 35% and HCl for 57% and in S3.8.1, HCl and NaOCl combined account for 96% and wind electricity use accounts for merely 2%. As for construction, its impact increases with increase in the wind plant capacity due to increase in number of turbines; however, it remains minimal compared to operation. For all off-grid scenarios, batteries contribute less to construction than turbine construction and network connection.

b. Mineral extraction

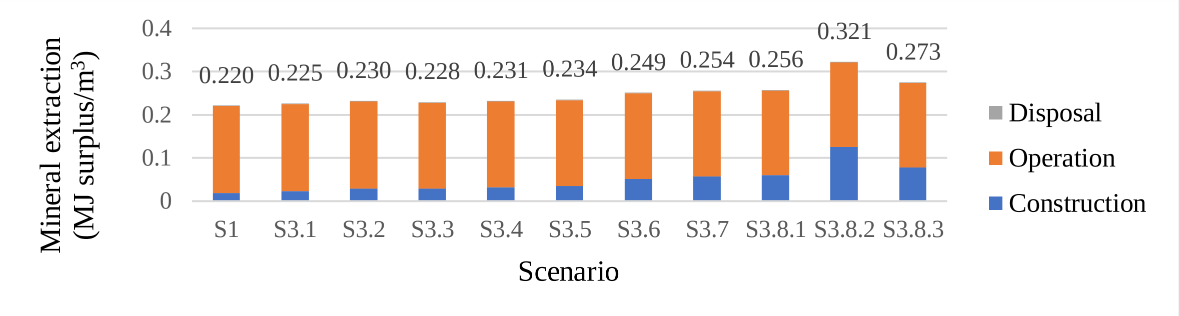

Figure 26 Mineral extraction wind

Mineral extraction increases with increase of % wind. S1 has a value of 0.22 MJ surplus/m^3 and this value increases by a maximum of 16% for on-grid scenarios and 46% for off-grid scenarios (0.254 MJ surplus/m^3 in S3.7 and 0.321 MJ surplus/m^3 in S3.8.2). For this category, impact from operation decreases as % wind increases, but that from construction increases more significantly causing a net increase. The reason behind this is that the main contributor in operation is chemical use and not electricity consumption (S1: 74% HCl, 19% electricity); therefore, replacing the grid with RE will not have significant impact in reducing mineral extraction. As for construction, the increased impact is due to the increase in number of turbines and more particularly the use of steel and copper in the nacelle. For off-grid scenarios, the increase in construction is more pronounced because batteries play a significant role, accounting for almost 38% (about 2.4 million MJ surplus/plant) of construction versus 60% (6.5 million MJ surplus/plant) due to wind turbine construction. Despite the increasing trend in mineral extraction, S3.3 displays a lower value than S3.2 due to the different turbines used. For both turbines, the main materials contributing are copper and steel; however, the difference in quantities is responsible for the difference in values.

c. Non-renewable energy

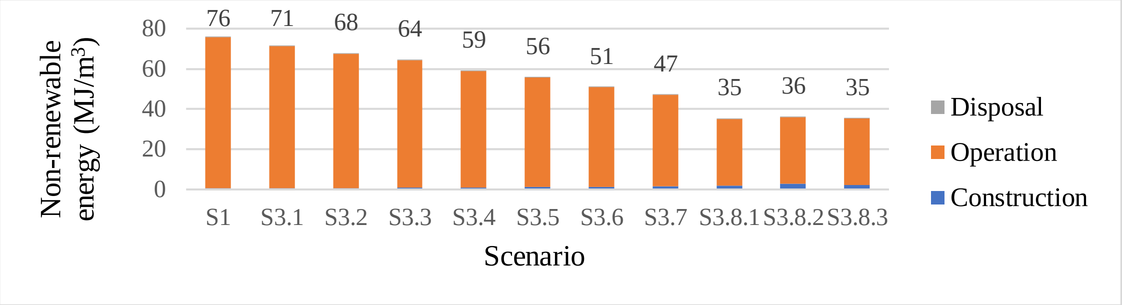

Figure 27 Non-renewable energy wind

Operation is the major contributor to non-renewable energy for all scenarios, ranging from 99% of the total in S1 to 92% in S3.8.2. Non-renewable energy is 76 MJ primary/m^3 in S1 and decreases by a maximum of 38% for on-grid scenarios to a value of 47 MJ primary/m^3 in S3.7 and 54% for off-grid scenarios to a value of 35 MJ primary/m^3 in S3.8.1. For operation in S1, 56% is due to electricity use and 40% due to HCl. For all scenarios, HCl becomes the main contributor in operation (ranging from 74% to 76%). For electricity consumption, both wind energy and the grid contribute to mineral extraction; whereby the grid is responsible for the higher impact in S3.1 up to S3.5. In S3.6, wind energy has a higher impact than the grid and it further increases as % wind increases beyond 60%. The contribution of wind energy is attributed to the increased use of lubricating oil for maintenance with the increase in number of turbines.

d. Ecotoxicity (aquatic and terrestrial)

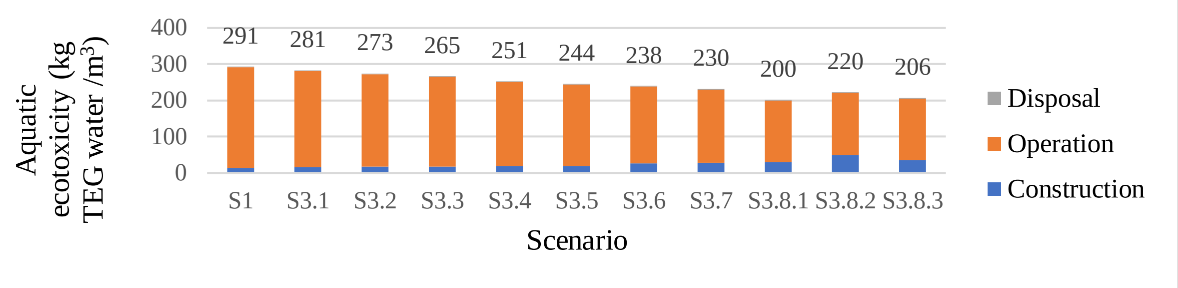

Figure 28 Aquatic ecotoxicity wind

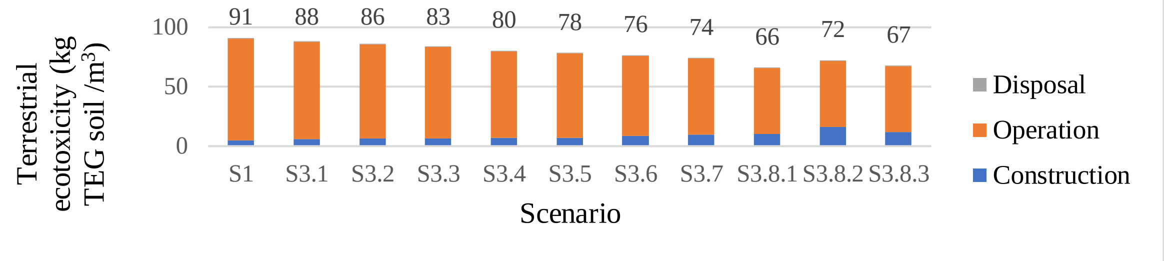

Figure 29 Terrestrial ecotoxicity wind

For aquatic and terrestrial ecotoxicity, the maximum reduction that could be achieved from the baseline scenario was 21% and 19% (for aquatic and terrestrial ecotoxicity respectively) when combining wind energy with the grid, in S3.7. Terrestrial ecotoxicity decreased from 91 kg TEG soil/m^3 (S1) to 74 kg TEG soil/m^3 (S3.7) and aquatic ecotoxicity decreased from 291 kg TEG water/m^3 (S1) to 230 kg TEG water/m^3 (S3.7). As for off-grid scenarios, the maximum reduction that could be achieved was 31% for aquatic ecotoxicity and 28% for terrestrial ecotoxicity, both in S3.8.1, with values of 200 kg TEG water /m^3 and 66 kg TEG soil/m^3. The reduction in this category, despite being noticeable, is not very significant because initially (in S1), the load in operation is equally distributed between chemical use and electricity consumption (50%-50%); as the renewable fraction increases, it decreases the portion of the impact that is due to electricity, but the impact from HCl remains. Additionally, the impact due to construction (despite being the smaller fraction: reaching a maximum of 23% among all scenarios) increases with plant capacity due to increase in number of turbines and number of batteries for off-grid scenarios. For both S3.8.1 and S3.8.3, turbines (more specifically steel, copper and road construction to provide access to the turbines) contribute more than batteries while for S3.8.2, the inverse is true.

e. Human toxicity (carcinogens and non-carcinogens)

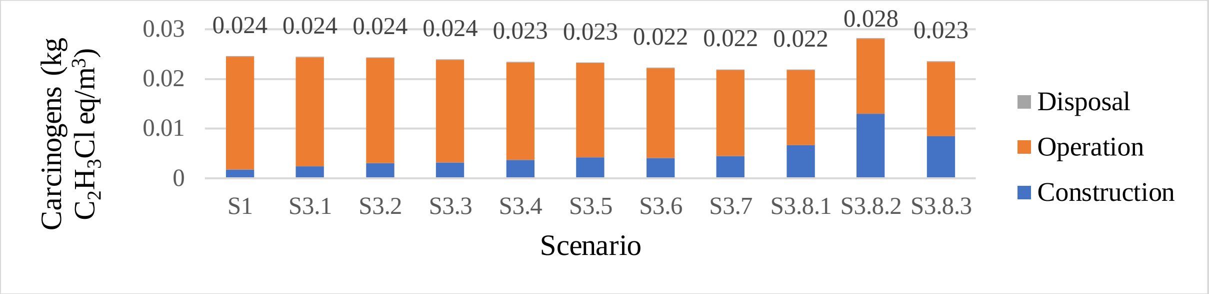

Figure 30 Carcinogens wind

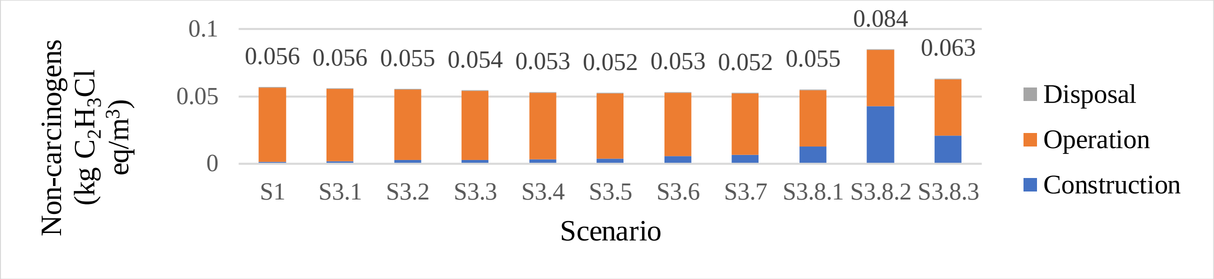

Figure 31 Non-carcinogens wind

Carcinogens and non-carcinogens in S1 have values of 0.024 kg C_2H_3Cl eq/m^3 and 0.056 kg C_2H_3Cl eq/m^3 respectively. The reduction in both categories for on-grid scenarios compared to the baseline scenario is very minimal (maximum of 11% for carcinogens and 8% for non-carcinogens); this is attributed to the fact that within operation, the bigger portion corresponds to HCl and not electricity (S1: carcinogens: 58% HCl, 36% electricity; non-carcinogens: 58% HCl, 31% electricity). In S3.7, the breakdown of impact from operation changes to 69% HCl, 14% grid for carcinogens and 70% HCl, 11% grid for non-carcinogens. The impact from construction increases with increase in % wind and consequently plant capacity. This causes a net increase in carcinogens in S3.8.2 reaching a value of 0.028 kg C_2H_3Cl eq/m^3 (15% increase as compared to S1) and non-carcinogens in S3.8.2 and S3.8.3 with values of 0.084 (50% increase) and 0.063 kg C_2H_3Cl eq/m^3 (11% increase) respectively. Construction increases 7-fold for carcinogens and 30-fold for non-carcinogens in S3.8.2, with batteries accounting for 70% of carcinogens (of construction) and 90% of non-carcinogens. Turbine construction is also responsible for a significant portion of the load and this is evident when observing that SWRO plant alone of 0.001735 kg C_2H_3Cl eq for carcinogens and 0.001408 kg C_2H_3Cl eq for non-carcinogens. However, when building a 16.8 MW plant (S3.7) carcinogens increase by 160% to 0.004516 kg C_2H_3Cl eq and non-carcinogens by 370% to 0.006628 kg C_2H_3Cl eq.

f. Air impacts (organics, inorganics, ionizing radiation, ozone depletion)

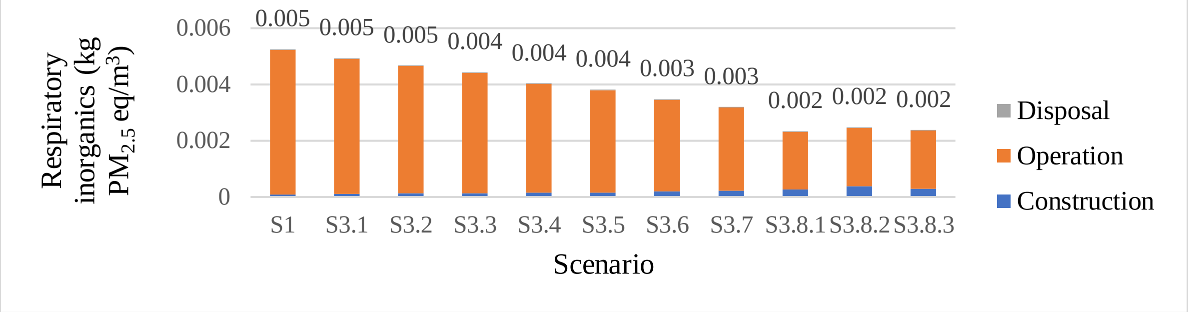

Figure 32 Respiratory inorganics wind

Respiratory inorganics amounted to 0.005 kg $PM_{2.5}$ eq/m^3 in S1 and remained constant in S3.1 and S3.2. This value decreases by a maximum of 40% for on-grid scenarios to a value of 0.003 kg $PM_{2.5}$ eq/m^3 and further decreases by a maximum of 55% for off-grid scenarios to 0.002 kg $PM_{2.5}$ eq/m^3. The change in respiratory inorganics is not very evident for scenarios with close wind %; however, it is quite significant over larger renewable fractions. The larger portion of respiratory inorganics is from operation (S1: 98%, S3.7: 93%, S3.8.2: 84%). Within operation, electricity use has a bigger impact than chemical use (S1: 60% grid, 40% chemicals); accordingly, in S3.7 (70% wind), the load shifts to 70% chemical use and 30% grid. A further shift in breakdown of the impact is observed in all off-grid scenarios whereby 98% of the load is cause by chemicals and 2% by wind. Increase in construction with increase of %

wind, despite being very pronounced, has very minimal values compared to operation. S3.8.2 (maximum value for construction between all scenarios) displays a 387% increase in construction compared to S1 and almost 60% decrease in operation; however, the values remain significantly apart with operation being 5-fold the value for construction (construction:0.000393 kg $PM_{2.5}$ eq/m^3s, operation: 0.002 kg $PM_{2.5}$ eq/m^3).

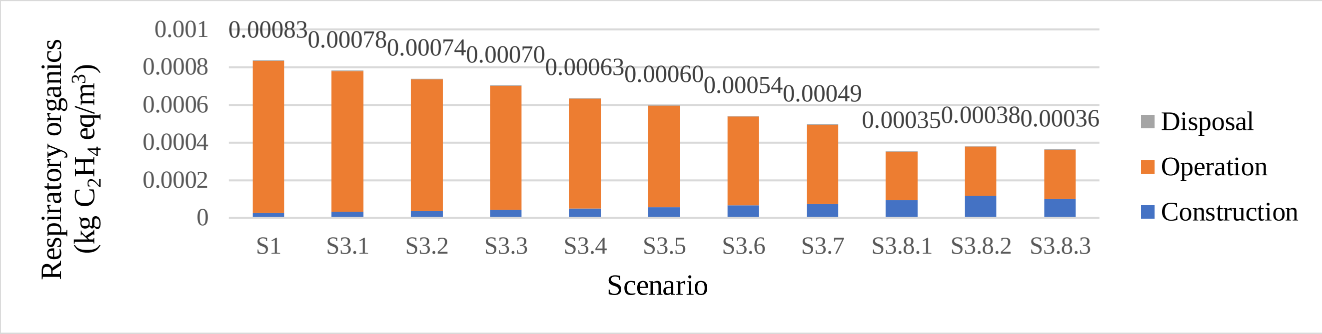

Figure 33 Respiratory organics wind

Respiratory organics in S1 have a value of 0.00083 kg C_2H_4 eq/m^3 and were reduced by a maximum of 41% for on-grid scenarios, reaching a value of 0.00049 kg C_2H_4 eq/m^3 in S3.7. As for off-grid scenarios, the impact could be reduced by 58% to 0.00035 kg C_2H_4 eq/m^3 in S3.8.1. Operation is the main contributor to respiratory inorganics accounting for 97%, 85% and 74% in S1, S3.7 and S3.8.1 respectively. This change in contribution percentage is due to decrease in impact from operation and increase of that from construction. The breakdown of operation goes from 70% grid, 30% chemicals in S1 to 30% grid, 70% chemicals in S3.7 and 100% chemicals in all off-grid scenarios. The increase due to construction goes from an initial 2.5E-05 kg C_2H_4 eq/m^3 in S1 to 7.35E-05 kg C_2H_4 eq/m^3 in S3.7 and 9.24E-05 kg C_2H_4 eq/m^3 in S3.8.1. Construction in S3.8.2 is even more pronounced with a value of 0.00012 kg C_2H_4 eq/m^3. Within construction, the main contributor is turbine construction and more specifically road excavation to provide access to the power plant, followed by the use of steel and glass fiber reinforced plastic. For off-grid scenarios, batteries do play a significant role in increasing the impact from construction; however, turbine construction has a higher contribution.

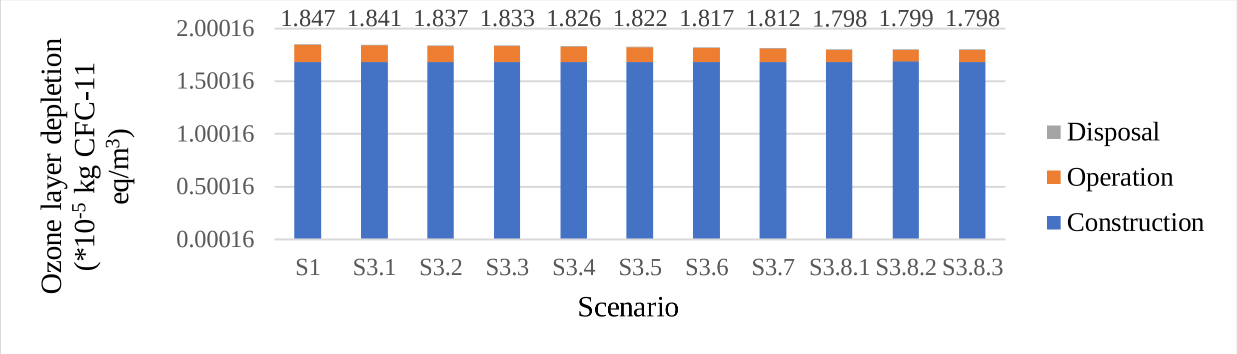

Figure 34 Ozone layer depletion wind

Ozone layer depletion ranges from 1.847E-05 kg CFC-11 eq/m^3 in S1 to 1.812E-05 kg CFC-11 eq/m^3 in S3.7 and 1.798E-05 kg CFC-11 eq/m^3 in S3.8.1 and S3.8.1. The reduction in this category is very minimal (maximum 3%). This is because in all scenarios, construction contributes about 91-94% and within construction, SWRO plant contributes 100% to the load (more specifically membrane production) compared to the wind plant. Accordingly, increase in wind plant capacity and even battery use, although significant within the wind plant construction, cause very insignificant increases in ozone layer depletion.

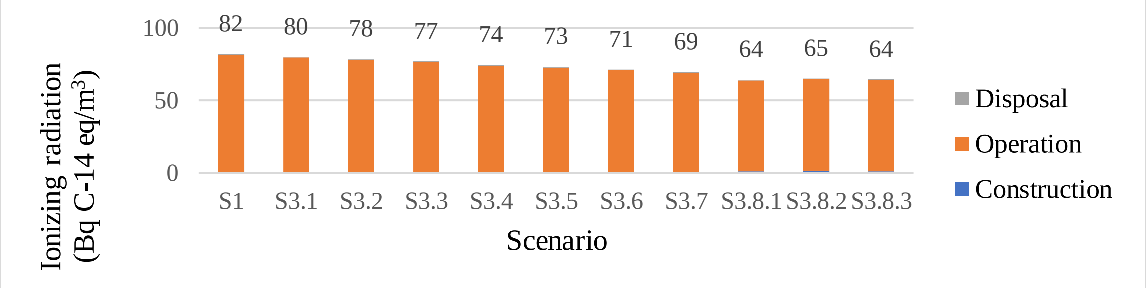

Figure 35 Ionizing radiation wind

Ionizing radiation in S1 is 82 Bq C-14 eq/m^3 and it decreases as % wind increases reaching a minimum value of 69 Bq C-14 eq/m^3 for on-grid scenarios (S3.7) and 64 Bq C-14 eq/m^3 for off-grid scenarios (S3.8.1 and S3.8.3). Operation accounts for 100% of the impact in S1 and very minimally decreases to 97% in S3.8.2, as construction slightly increases. The reason for this is that in S1 operation phase, 23% of the ionizing radiation comes from electricity and 74% from HCl. As % wind increases, % electricity use from the grid decreases, thus switching the impact in the 3 off-grid scenarios into 100% chemical use. Within construction, SWRO plant initially has a higher impact than the wind plant (S3.1: 74% SWRO plant, 26% wind plant); however, as the size of the wind plant increases, the load is switched (S3.7: 25% SWRO plant, 75% wind plant). For off-grid scenarios S3.8.2, despite having a smaller capacity (17 MW) compared to S3.8.1 and S3.8.3 (21 MW and 25 MW respectively) has a higher impact because of the bigger number of batteries used.

g. Acidification and eutrophication (aquatic acidification, aquatic eutrophication, terrestrial acidification/nutrification)

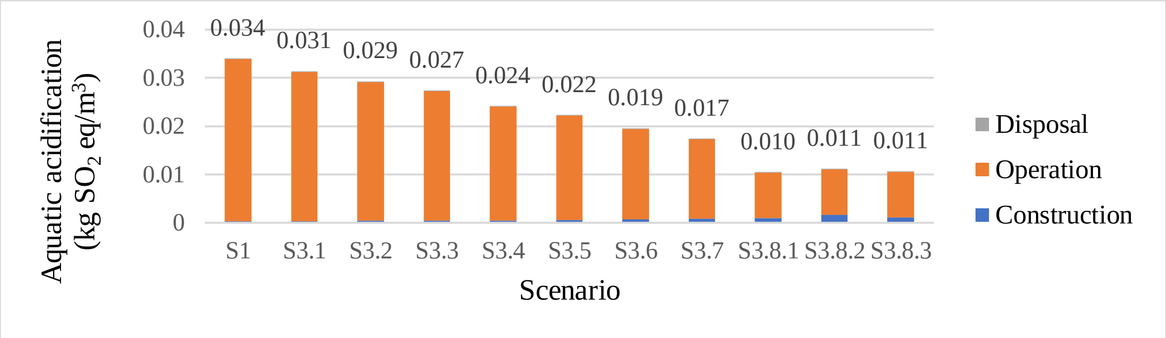

Figure 36 Aquatic acidification wind

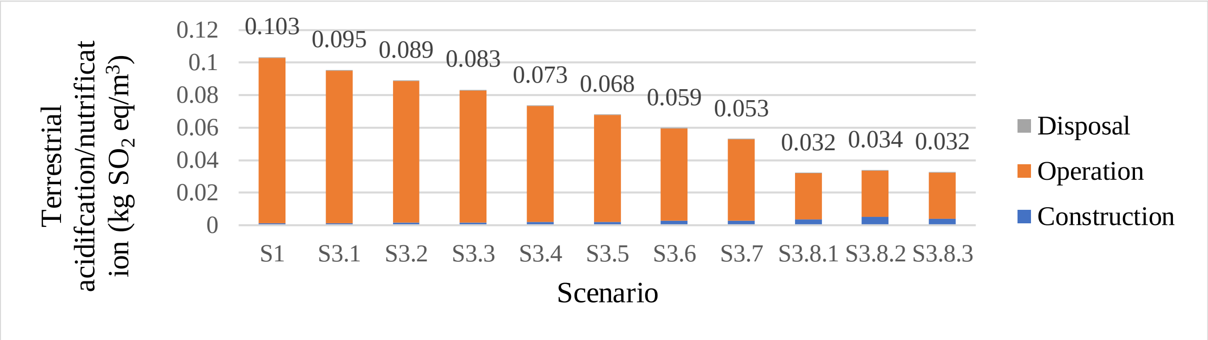

Figure 37 Terrestrial acidification/nutrification

Aquatic acidification and terrestrial acidification/nutrification will be interpreted together because they follow similar trends. In both categories, impact could be reduced by a maximum of 49% from the baseline scenario for on-grid scenarios and by 70% for off-grid scenarios (Aquatic acidification: S1: 0.034 kg SO_2 eq/m^3, S3.7: 0.017 kg SO_2 eq/m^3, S3.8.1: 0.01 kg SO_2 eq/m^3; Terrestrial acidification/nutrification: S1: 0.103 kg SO_2 eq/m^3, S2.5: 0.053 kg SO_2 eq/m^3, S3.8.1: 0.032 kg SO_2 eq/m^3). The major contributor in both categories for all scenarios is operation, accounting for almost 99% of the overall load in S1 and 85% in S3.8.2. This change is because as % wind increase the impact from operation decreases as that from construction increases. Even so, the increase in construction is not as impactful as the decrease in operation, resulting in a net decrease in impact. The maximum increase in construction was observed in S3.8.2 due to increased number of turbines and high number of batteries used, reaching values of 0.0017 kg SO_2 eq/m^3 for aquatic acidification and 0.00512 kg SO_2 eq/m^3 for terrestrial acidification/nutrification. This is a 560% increase from the construction in S1. As the impact from operation decreases by 72% from the baseline scenario reaching values of 0.00937 kg SO_2 eq/m^3 for aquatic acidification and 0.0284 kg SO_2 eq/m^3 for terrestrial acidification/nutrification, the values remain significantly higher than those from the construction phase.

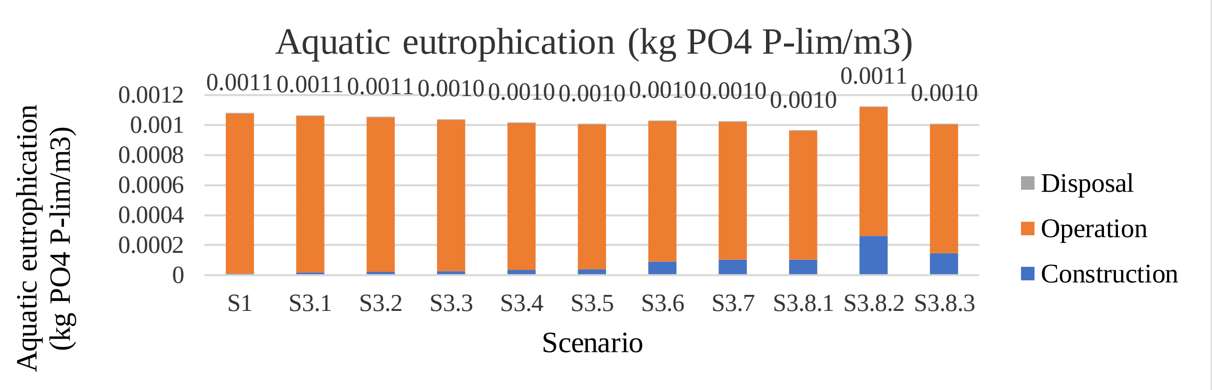

Figure 38 Aquatic eutrophication wind

Aquatic eutrophication has a value of 0.00108 kg PO_4^{3-}/m^3 in S1. For all scenarios, wind energy causes a decrease in aquatic eutrophication except for S3.8.2. Among on-grid scenarios, this value decreases incrementally by a maximum of 7% to a value of 0.001 kg PO_4^{3-}/m^3 in S3.5, after which the impact begins to increase again, though remaining lower than the value in the baseline scenario. Among off-grid scenarios, a decrease is observed in S3.8.1 (-11%) and S3.8.3 (-7%), while S3.8.2 displays an increase (+4%). The impact from operation decreases as % wind increases; however, the decrease is minimal because the impact in S1 is broken down into 26% grid and 74% chemicals, i.e. electricity consumption constitutes the lower portion. As for construction, it increases with increase of % wind which is accompanied with increase in turbine capacity. The reason for S3.6 and scenarios that follow not following the trend of S3.5 and the scenarios that precede is the use of different turbines with different capacities (4.2MW versus 2MW), where construction experiences a 125% jump in aquatic eutrophication when shifting. More specifically, the 4.2MW turbine has a heavier load caused by use of copper in the nacelle and reinforcing steel in the tower (which is made of concrete and steel tube) and foundation, as opposed to the 2MW tower which is made of steel. The increased load in S3.8.2 is caused by both increased turbine capacity (20%) and more significantly battery use (78%), while for the other off-grid scenarios, the lower number of batteries results in a different breakdown (S3.8.1: 56% turbine, 41% batteries; S3.8.3: 38% turbine, 60% batteries).

h. Land occupation

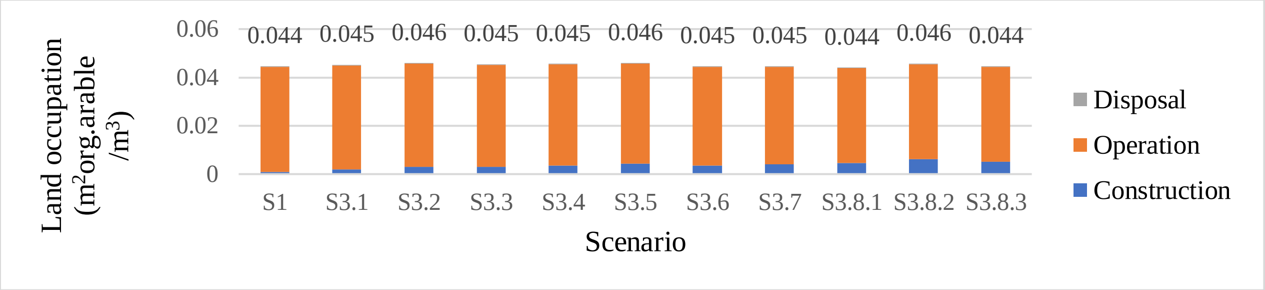

Figure 39 Land occupation wind

Land occupation slightly increases in all scenarios compared to the baseline scenario. S1 has a value of 0.044 m^2 org arable land-eq/m^3, which increases to a maximum value of 0.046 m^2 org arable land-eq/m^3 (3% increase) in both on-grid scenarios (S3.5) and off-grid scenarios (S3.8.2). Operation accounts for the higher portion of the impact in this category for all scenarios; however, as % wind increases operation decreases very minimally, and construction increases, thus causing a net increase in impact. Within operation, the high impact is due to chemical use and not electricity (74% HCl, 11% electricity for S1). Within construction, the load is more pronounced for wind plant construction than SWRO plant construction. Within the wind plant, increase in load is caused to a greater extent by wind turbine construction than network connection for on-grid scenarios, and more by wind turbine construction than batteries for off-grid scenarios. The impact from wind turbine construction is mainly caused by road excavation to provide access to the power plant and excavation to build the foundation for the turbines. Scenario S3.6 and the ones that follow have slightly lower impact than the previous ones because road excavation is the same among the scenarios; it is based on number of turbines regardless of capacity.

4.2.3. AD results

a. Global warming

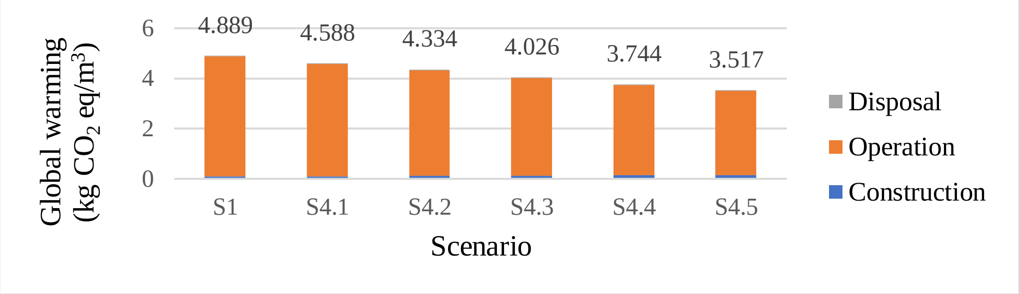

Figure 40 Global warming AD

Global warming has a value of 4.889 kg CO_2 eq/m^3 in S1. This value decreases as the renewable fraction increases until it reaches a value of 3.517 kg CO_2 eq/m^3 (28% maximum reduction) in S4.5. In all scenarios, operation is the major contributor to global warming (S1: 98% operation, 2% construction; S4.5: 96% operation, 2% construction). Within operation, S1 is broken down into 64% electricity, 36% chemicals; as % AD increases the distribution slowly shifts to 48% grid, 1.5% AD and 50% chemicals. The emissions from AD are attributed to burning the biogas. The impact from construction is minimal across all scenarios. Though it increases significantly as the size of generator increases (67% increase from S1 to S4.5), its value remains insignificant compared to operation. Within construction, common components contribute more significantly than electrical components (85% and 15% respectively) and within common components the highest impact is due to maintenance.

b. Mineral extraction

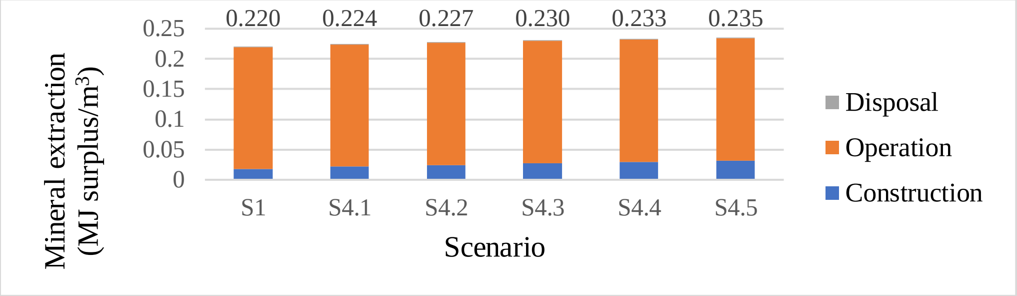

Figure 41 Mineral extraction AD

Mineral extraction increases as % AD increases, whereby S1 has a value of 0.22 MJ surplus/m^3 and this value increases to a maximum of 0.235 MJ surplus/m^3 (7% increase). Although operation is the main contributor to mineral extraction in all scenarios, the impact from both operation and construction increases in this category. In S1, operation is broken down into 19% electricity and 81% chemicals. As the fraction of biogas increases, its impact increases and that from the grid decreases; however, the increase in biogas is on average 47% which is much higher than the average 12% decrease in grid, thus increasing mineral extraction overall. Within construction, despite the fact that SWRO plant constitutes the bigger portion, the increase in generator size with increase in % biogas increases the impact.

c. Non-renewable energy

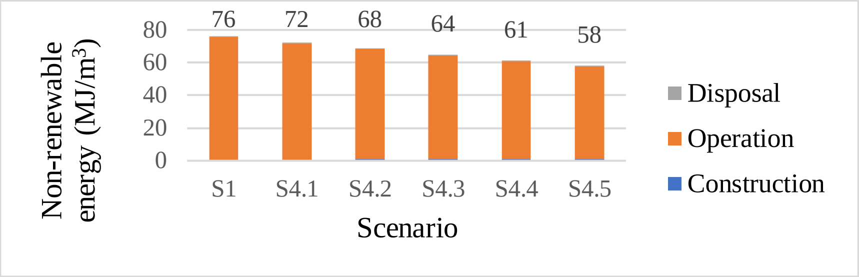

Figure 42 Non-renewable energy AD

Non-renewable energy decreases as %AD increases. It begins at 76 MJ primary/m^3 in S1 and decreases by a maximum of 24% to a value of 58 MJ primary/m^3 in S4.5. Operation constitutes 98-99% of the impact in all scenarios. For operation in S1, 56% of the impact is due to electricity and 44% due to chemicals. In S4.5, the impact from the grid decreases and the breakdown becomes 39% grid and 58% chemicals. Though minimal, within construction, the impact is highest from the SWRO plant followed by generators followed by construction of the AD unit. Within generators, the highest impact is due to maintenance.

d. Ecotoxicity (aquatic and terrestrial)

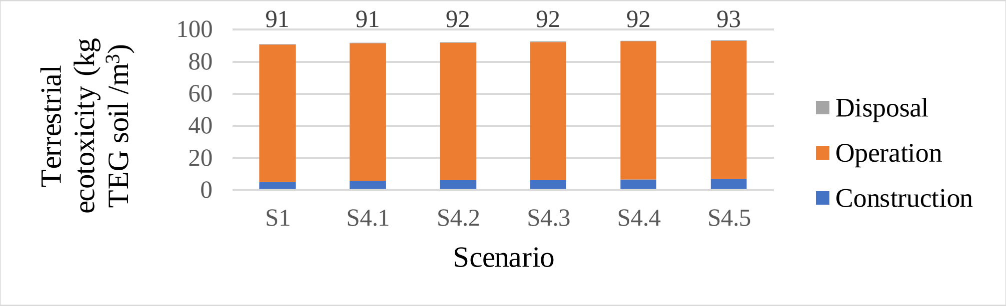

Figure 43 Terrestrial ecotoxicity AD

Terrestrial ecotoxicity increases with increase of % AD. The baseline scenario S1 has a value of 91 kg TEG soil/m^3; this value increases gradually to a maximum value of 93 kg TEG soil/m^3 (2% increase). Although both construction and operation contribute to the overall increase in terrestrial ecotoxicity, construction is to a greater extent responsible for the increase (38% increase from S1 to S4.5 as opposed to 0.34% increase for operation). Within operation, the impact in S1 is divided into 50% electricity and 50% chemicals. As % AD increases, the impact from the grid decreases but that from biogas increases, thus making up for the decrease. As such, the distribution of electricity use (combined AD and grid) and chemical use remains 50-50 for all scenarios. Within construction, increase in generator size causes an increase in their impact more specifically due to maintenance and to a lesser extent control cabinet and gas motor. However, SWRO plant construction has the bigger portion of the impact in all scenarios, ranging from 90% in S4.1 to 72% in S4.5.

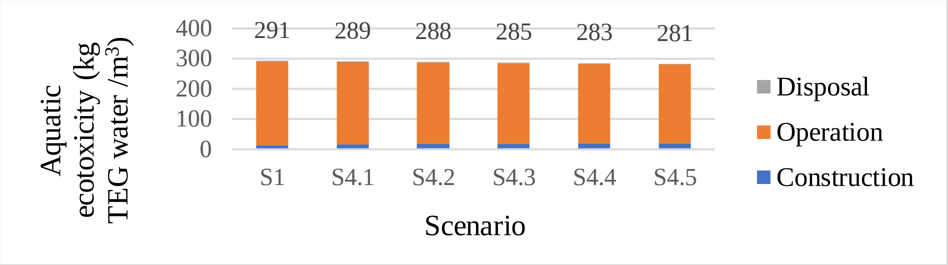

Figure 44 Aquatic ecotoxicity AD

Aquatic ecotoxicity begins at 291 kg TEG water/m^3 in S1 and experiences a gradual decrease with increase of renewable fraction until it reaches a value of 281 kg TEG water/m^3 in S4.5 (4% decrease). Operation accounts for the higher portion of the impact for all scenarios, ranging from 95% in S1 to 93% in S4.5. Within operation, the breakdown in S1 is 49% electricity, 51% chemicals; as % AD increases, impact from biogas increases at a slower rate than the decrease in grid, thus causing a net decrease in impact. As for construction, the impact increases with increase of % AD, but the higher portion remains because of the SWRO plant and not the generators and AD unit.

e. Human toxicity (carcinogens and non-carcinogens)

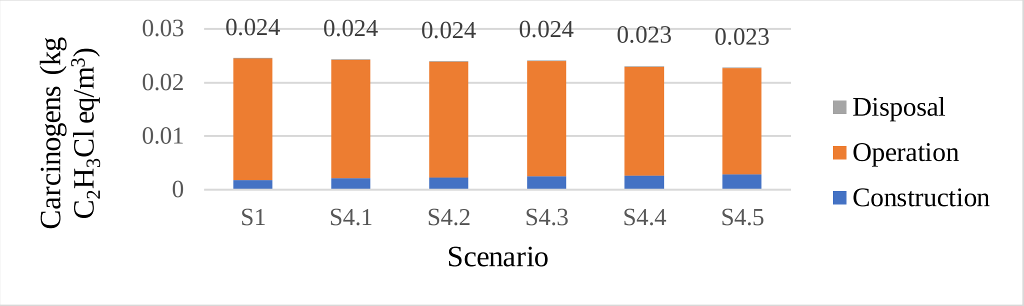

Figure 45 Carcinogens AD

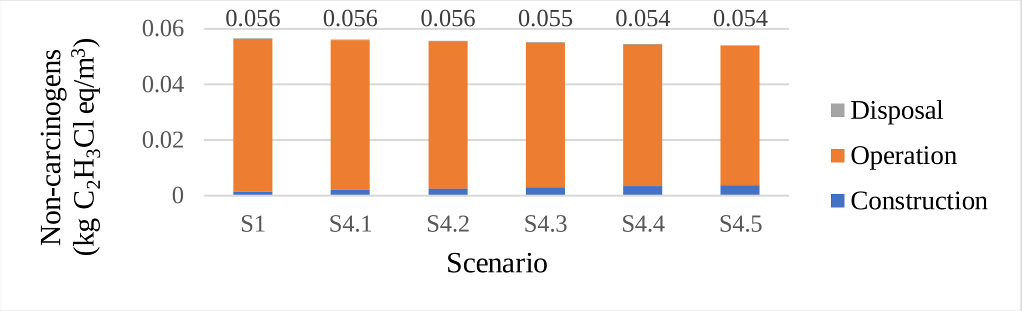

Figure 46 Non-carcinogens AD

Carcinogens and non-carcinogens in S1 have values of 0.024 kg C_2H_3Cl eq/m^3 and 0.056 kg C_2H_3Cl eq/m^3 respectively. This value decreases in both categories as renewable fraction increases. The maximum reduction in carcinogens is 7% reaching a value of 0.023 kg C_2H_3Cl eq/m^3, and that in non-carcinogens is 4% reaching a value of 0.054 kg C_2H_3Cl eq/m^3 in S4.4 and S4.5. The main contributor in both categories is operation. In S1, carcinogens are broken down into 7% construction and 93% operation and non-carcinogens into 2% construction and 98% operation. As renewable fraction increases, the breakdown shifts into 12% construction, 87% operation for carcinogens and 7% construction, 93% operation for non-carcinogens. The reason for the minimal decrease in both carcinogens and non-carcinogens is that despite the decrease in impact from operation (overall 13% for carcinogens and 9% for non-carcinogens) and the faster increase from construction (overall 63% for carcinogens, 166% for non-carcinogens), the values for operation are on average 9-fold the ones from construction for carcinogens and 12-fold for non-carcinogens. Within operation, the impact from AD increases at a smaller rate than the decrease in grid (average 12% decrease for both carcinogens and non-carcinogens, average 47% increase in carcinogens and 354% increase in non-carcinogens for AD), thus causing a net decrease in impact, which is more evident for non-carcinogens. Within construction, at low renewable fractions, the SWRO plant has a higher impact than the generator and AD unit; however, as % AD increases the impact shifts such that an almost equal contribution is observed in S4.5 for both carcinogens and non-carcinogens. The main contributors from the AD unit are cast iron and reinforcing steel for both carcinogens and non-carcinogens and additionally copper for non-carcinogens. For carcinogens, the highest contributor within generator unit is maintenance and gas motor and to a lesser extent sound insulation. For non-carcinogens, the highest contributor within generator unit is the generator itself.

f. Air impacts (organics, inorganics, ionizing radiation, ozone depletion)

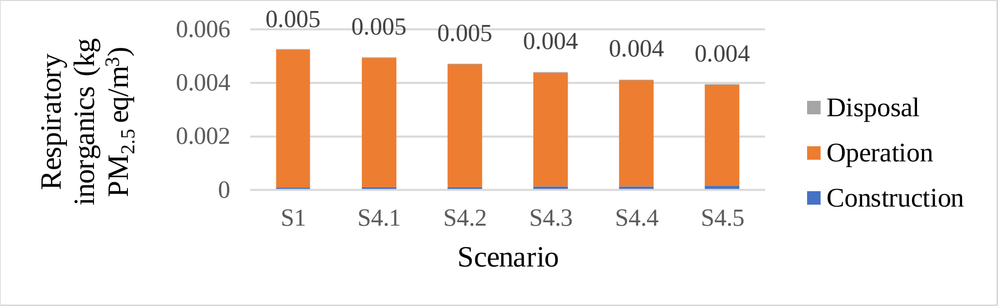

Figure 47 Respiratory inorganics AD

Respiratory inorganics amount to 0.005 kg $PM_{2.5}$ eq/m^3 in S1 and remain constant in S4.1 and S4.2. This value decreases by a maximum of 25% to a value of 0.004 kg $PM_{2.5}$ eq/m^3 in S4.3 till S4.5. The change in respiratory inorganics is not very evident for scenarios with close wind %; however, it is significant over larger renewable fractions. The larger portion of the impact is from operation (S1: 98%, S3.7: 93%, S3.8.2: 84%). Within operation, electricity has a bigger portion of the impact compared to chemicals (S1: 60% grid, 40% chemicals); accordingly, in S4.5, the load shifts to

43% grid, 3% electricity from biogas and 54% chemicals. The impact from construction increases with increase in renewable fraction due to increase in generator size; however, not significantly enough to make up for the decrease in operation, whereby the values from operation remain on average 40 times the ones from construction. Within construction, SWRO causes the majority of impact in all scenarios.

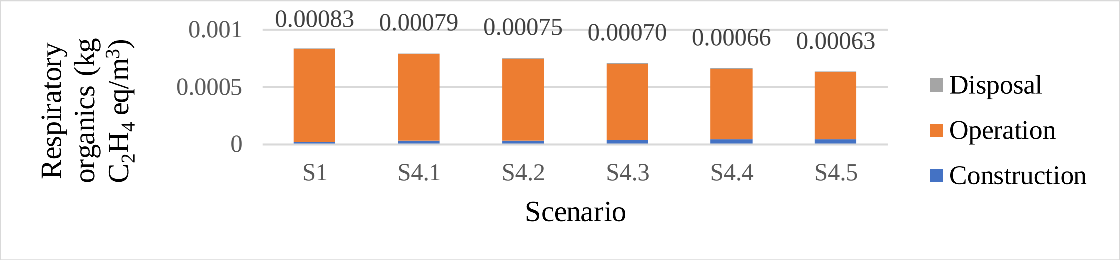

Figure 48 Respiratory organics

Respiratory organics in S1 have a value of 0.00083 kg C_2H_4 eq/m^3 and were reduced by a maximum of 24% reaching a value of 0.00063 kg C_2H_4 eq/m^3 in S4.5. Operation is the main contributor to respiratory organics accounting for 97% in S1 and 92% in S4.5. This change in contribution percentage is due to decrease in impact from operation and increase of that from construction. The breakdown of the operation phase goes from 70% grid, 30% chemical use in S1 to 50% grid, 7% AD and 43% chemicals in S4.5. Within construction, SWRO plant is responsible the bigger portion of the impact in all scenarios; however, as % AD increases, the distribution becomes almost equal (S4.5: 52% SWRO, 48% AD unit and generator). For AD unit, main contributors are cast iron followed by reinforcing steel and concrete. As for the generator, main contributors are maintenance, control cabinet, sound insulation and gas motor.

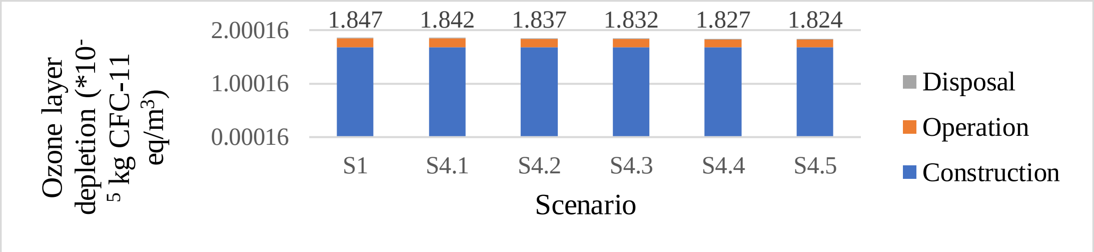

Figure 49 Ozone layer depletion AD

Ozone layer depletion begins at 1.847E-05 kg CFC-11 eq/m^3 in S1. The reduction in this category is almost negligible (maximum of 1%). This is because in all scenarios, construction contributes about 91-92% of the total environmental load and within the construction phase, the SWRO plant construction contributes 100% to the load. Membrane production is 100% responsible for the heavy load in this category.

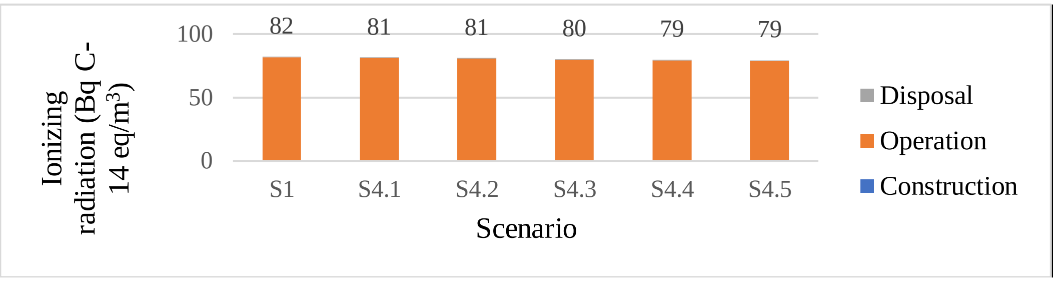

Figure 50 Ionizing radiation AD

Ionizing radiation in S1 is 82 Bq C-14 eq/m^3 and it decreases as % AD increases but very minimally. The maximum reduction is 3% reaching a value of 79 Bq C-14 eq/m^3 in S4.4 and S4.5. Operation accounts for 100% of the impact in S1 and very minimally decreases to 99% in S4.2 and the scenarios that follow. Within operation, HCl is responsible for the bigger portion of the impact (S1: 23% HCl, 74% grid) which justifies the minimal decrease in impact with increase of renewable percent. Although combining electricity from biogas with the grid achieved a 4% decrease in operation, this decrease is not significant enough to cause a notable decrease in impact, especially considering the increase in construction. Construction in S4.5 increases by 244% from S1, but its value remains significantly lower than that from operation (S4.5: operation: 78.06 Bq C-14 eq/m^3, construction: 0.69 Bq C-14 eq/m^3). For construction, generators cause the highest impact in S4.2 and the ones that follow, more specifically due to energy requirements of building the unit, air input/output unit and control cabinet.

g. Acidification and eutrophication (aquatic acidification, aquatic eutrophication, terrestrial acidification/nutrification)

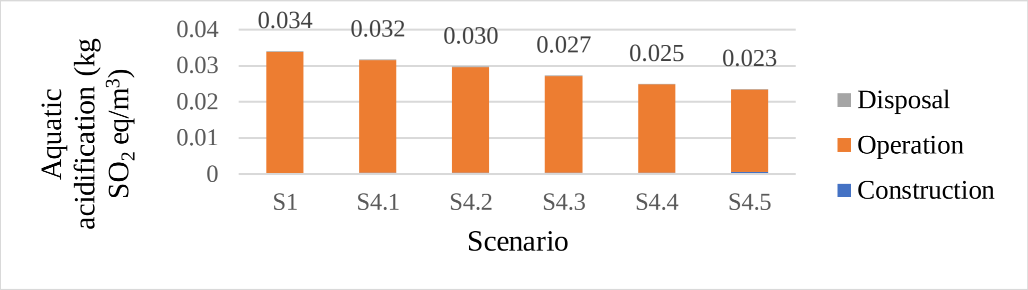

Figure 51 Aquatic acidification AD

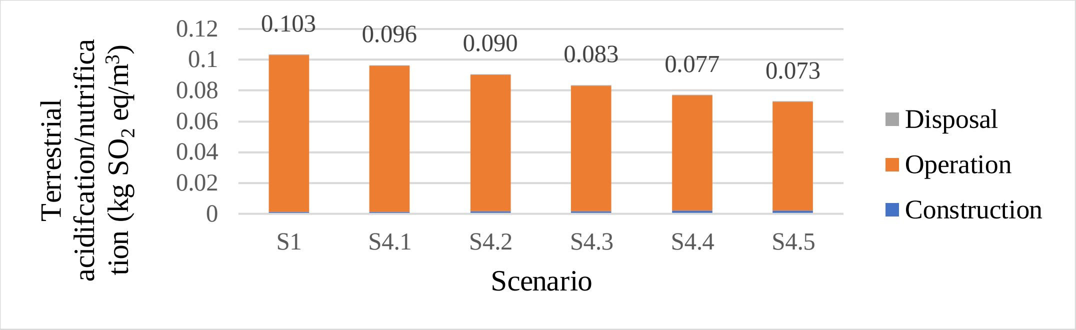

Figure 52 Terrestrial acidification/nutrification AD

Aquatic acidification and terrestrial acidification/nutrification will be interpreted together because they follow similar trends. In both categories, impact could be reduced by a maximum of 30% from the baseline scenario (Aquatic acidification: S1: 0.034 kg SO_2 eq/m^3, S4.5: 0.023 kg SO_2 eq/m^3; Terrestrial acidification/nutrification: S1: 0.103 kg SO_2 eq/m^3, S4.5: 0.073 kg SO_2 eq/m^3). The major contributor in both categories for all scenarios is the operation phase, accounting for almost 99% in S1 and 97% in S4.5. Within operation, the bigger portion of the impact is caused by electricity for both categories (S1: 73% electricity, 27% chemicals). Although the construction phase increases at a faster rate (Aquatic acidification: overall 125% increase; Terrestrial acidification/nutrification: overall 87% increase) than the decrease in operation (Aquatic acidification: overall 32% decrease; terrestrial acidification/nutrification: overall 30% decrease), operation remains more impactful on the overall value because it is on average 48 times construction in terrestrial acidification/nutrification and 59 times construction in aquatic acidification. The difference between the two categories lies in the distribution of the impact within construction whereby aquatic acidification begins with 72% SWRO plant in S1 and ends with 44% in S4.5 while terrestrial acidification/nutrification begins with 78% SWRO plant in S1 and ends with 53% in S4.5. For the AD unit, the impact is mainly caused by cast iron, reinforcing steel and concrete for both categories, and additionally copper for aquatic acidification. For generator unit, the impact is mostly caused by maintenance followed by control cabinet.

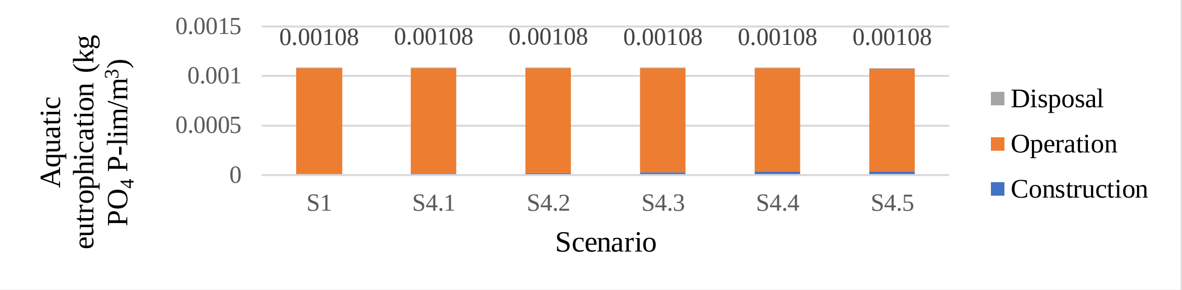

Figure 53 Aquatic eutrophication AD

Aquatic eutrophication has a value of 0.00108 kg PO_4^{3-}/m^3 in S1. This value remains constant for all scenarios; i.e. no reduction of impact was achieved. The breakdown of impact changes in every scenario, with operation carrying the bigger portion across all scenarios (ranging from 99% in S1 to 96% in S4.5). The reason behind this shift is that the impact from operation decreases with increase in %AD and that from construction increases proportionally, such that no net change occurs. Within operation, S1 is broken down into 74% chemicals and 26% electricity, which justifies the minimal decrease in impact with increase of renewable fraction (as electricity from biogas is also a contributor in this category). As for construction, the load in S4.1 is divided into 52% SWRO plant, 38% generator and 10% AD unit. As % AD increases, the generator increases in size and the load distribution in S4.5 shifts to 24% SWRO, 56% generators and 20% AD unit. For the generator unit, the main contributor is the construction of the generator itself. As for the AD plant, the main contributors are copper (almost 65%) and to a lesser extent reinforcing steel (18%) and cast iron (11%).

h. Land occupation

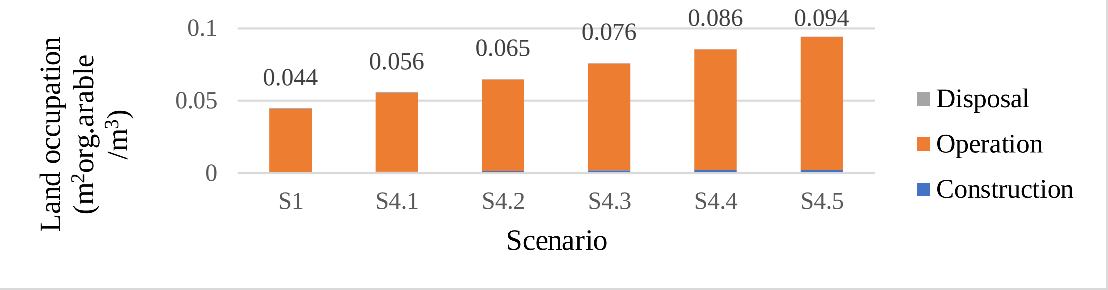

Figure 54 Land occupation AD

Land occupation increases significantly in all scenarios compared to the baseline scenario. S1 has a value of 0.044 m^2 org arable land-eq/m^3, which increases to a maximum value of 0.094 m^2 org arable land-eq/m^3 (111% increase) in S4.5. Operation accounts for the higher portion of the impact being between 97% and 98% for all scenarios. However, land occupation increases within both construction (195% increase) and operation (109% increase). Within operation, 89% of the impact is due to chemical use and not electricity in S1. Although adding renewable energy decreases the impact from the grid, land occupation due to electricity from biogas increases, thus causing an overall increase in operation load. As for construction, SWRO plant accounts for 65% of the load in S4.1. However, the load becomes equally distributed in S4.2 between SWRO plant and generator and AD unit combined, until it further shifts into 35% SWRO plant in S4.5. The reason behind the load increase in construction is bigger generator capacity and more specifically control cabinet and energy requirements. As for AD unit, main contributor to land occupation is land transformation for building the plant.

4.3. Comparison of the best scenarios

4.3.1. On-grid scenarios

For on-grid scenarios, S2.5, S3.7 and S4.5 display the best performance in almost all categories. The midpoint scores for these scenarios are found in figure 55.

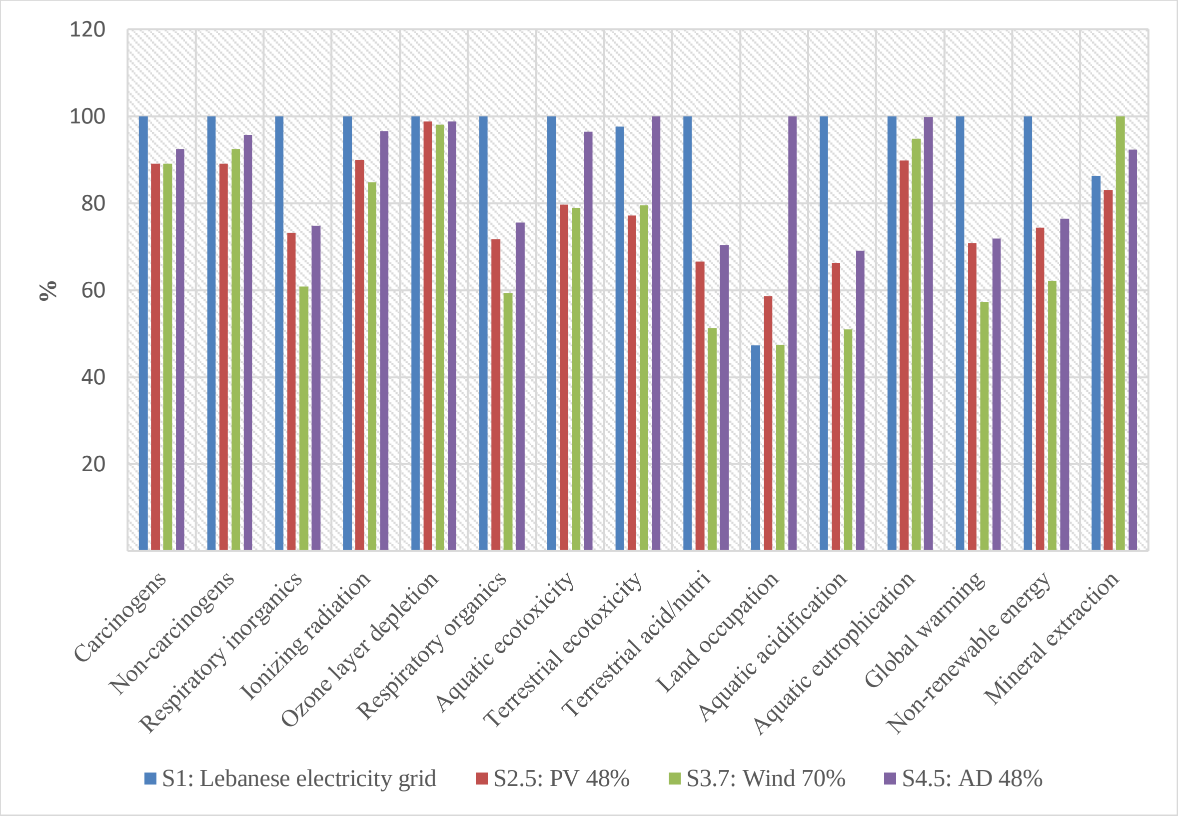

Figure 55 Comparison of best on-grid scenarios

Wind energy is the best performer in almost all categories except for non-carcinogens, aquatic ecotoxicity, aquatic eutrophication and mineral extraction in which PV is the best performer. Combination of AD with SWRO does not show ideal performance in any category. It is to be noted that S3.7 is characterized by 70% wind while S2.5 is characterized by 48% PV. When comparing equal renewable fractions for both wind and PV, the results could prove to be somewhat similar (values for S2.5 and S3.5 can be found in sections 4.1.1. and 4.1.2. respectively). However, for the case of Lebanon and more specifically the chosen region, the wind resource could yield higher fractions than solar energy. If a higher percentage of PV could be achieved, it is expected that it will be more advantageous than wind because 50% PV is already a better performer in some categories than 70% wind (figure 55). Figures 56 and 57 summarize respectively the endpoint results and the single point scores for the 4 scenarios that further prove wind energy to be the best performer.

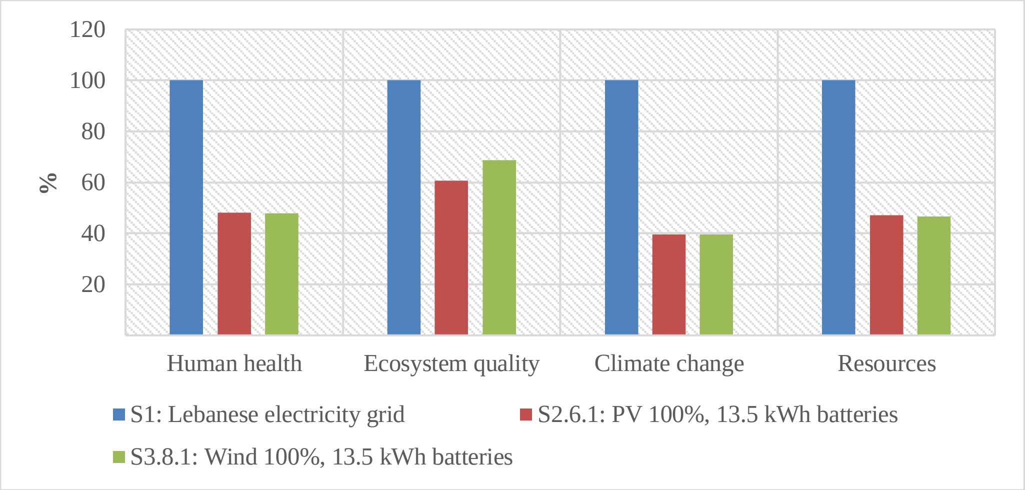

Figure 56 Endpoint results for best on-grid scenarios

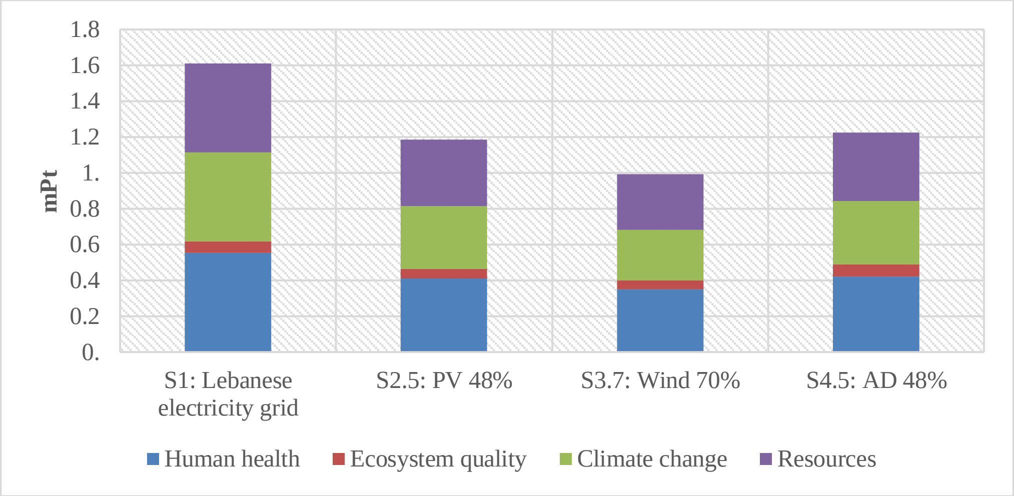

Figure 57 Single scores for best on-grid scenarios

4.3.2. Off-grid scenarios

Since AD does not include any off-grid scenario, only the best ones from PV and wind will be compared. S2.6.1 and S3.8.1 display the best performance in almost all categories. The scores for these scenarios are found in figure 58.

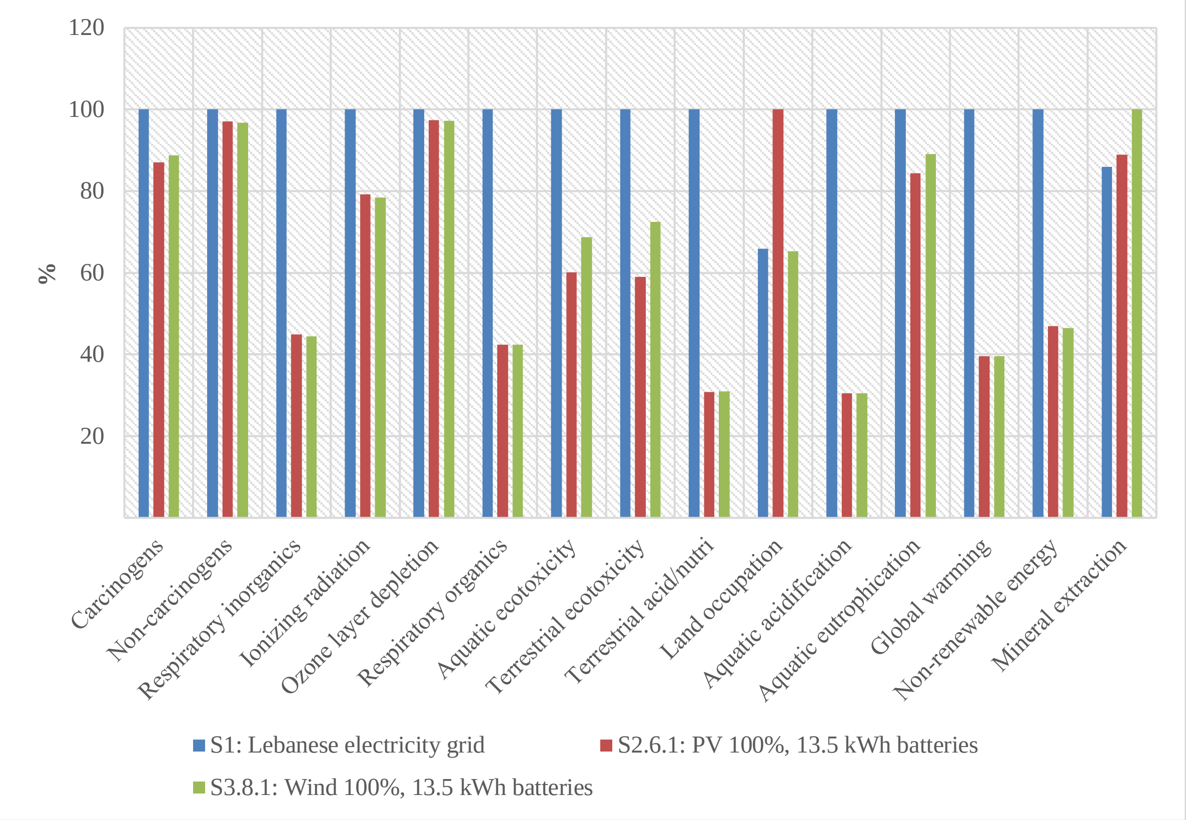

Figure 58 Comparison of best off-grid scenarios

PV and wind have similar scores in many impact categories (respiratory inorganics, ozone layer depletion, respiratory organics, aquatic acidification, terrestrial acidification/nutrification, global warming and non-renewable energy). PV displays better scores in carcinogens, aquatic and terrestrial ecotoxicity, land occupation, aquatic eutrophication and mineral extraction. Wind displays better scores in non-carcinogens and ionizing radiation. As such, PV is a better performer than wind in most categories when combining them with 13.5 kWh batteries. Figures 59 and 60 display respectively the endpoint results and single scores for both scenarios compared to the grid. Regarding the endpoint categories, PV and wind are quite comparable in all categories except ecosystem quality where wind is almost 13% higher. As for human health, climate change and resources, results for both scenarios are very similar with insignificant differences. Regarding the single scores, PV is only slightly better performing than wind with merely 0.0014 mPt difference (or 0.2%).

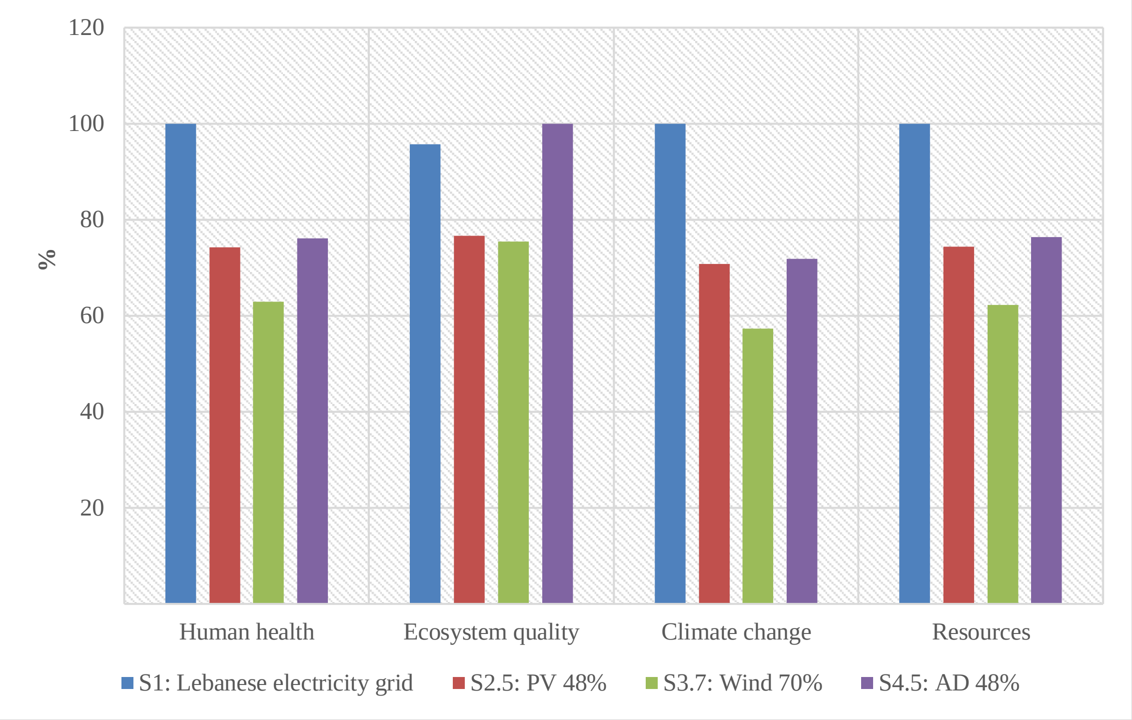

Figure 59 Endpoint results for best off-grid scenarios

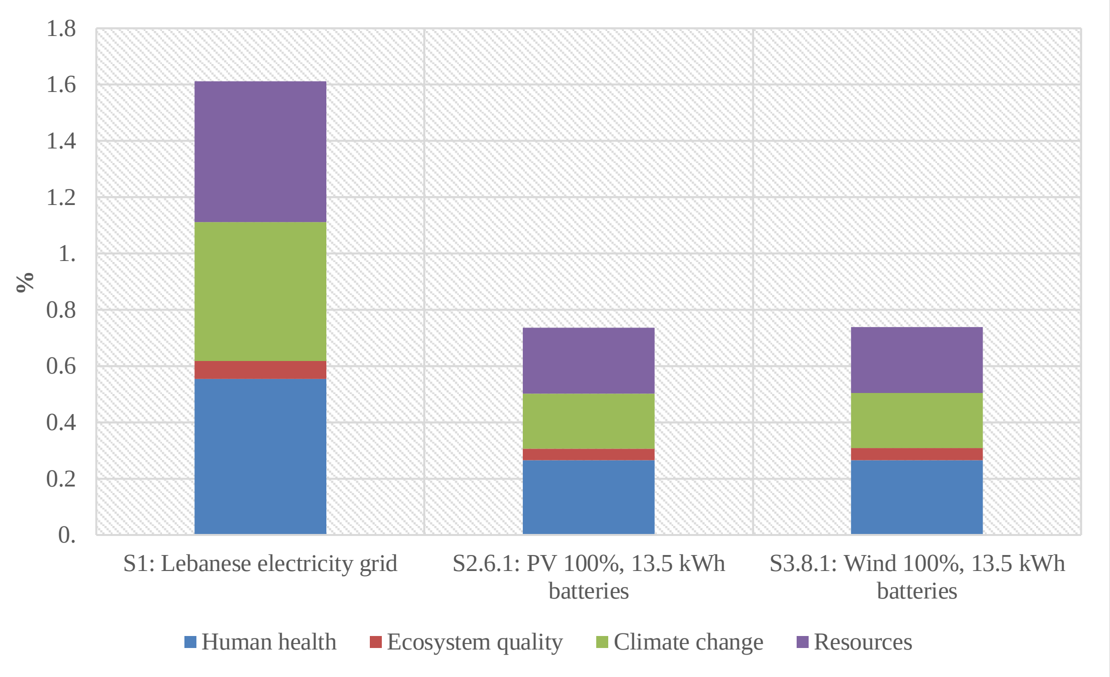

Figure 60 Single scores for best off-grid scenarios

4.4. Discussion

Table 17 summarizes the carbon footprint obtained for different literature studies. Discrepancies between the values are the result of many factors among which the most important are electricity consumption, electricity mix and system boundaries. Some plants consume more electricity than others especially ones with different source water salinity (BWRO is less energy intensive than SWRO), thus resulting in different carbon footprints. As for the electricity mix, it could be seen that different mixes can have widely variable carbon footprints whereby mixes with high percentages of oil and coal such as the plants considered by Wahidul K. Biswas (2009), Shahabi *et al.* (2013) and Zhou *et al.* (2011) have significantly higher footprints than the ones considered by Raluy *et al.* (2006), Munoz & Fernandez-Alba (2008) and Beery *et al.* (2012) which run on bigger shares of natural gas and renewable energy (like hydropower and nuclear). The system boundaries that are considered also have significant impact on the results whereby some studies do not take construction and O&M into account, thus obtaining lower footprints. It should also be noted that most of the studies considered either do not use any acid for pH adjustment or use sulfuric acid instead of hydrochloric acid which could yield lower footprints. The high carbon footprint obtained in this study is due to firstly, the Lebanese electricity grid which is almost 97% oil and 3% hydropower and natural gas and secondly, the use of HCl and not H_2SO_4.

Table 17 Comparison of carbon footprint to literature

Reference	**Method**	**Plant type**	**Capacity (m^3/day)**	**Electricity (kWh/m^3)**	**Carbon footprint (kg CO_2 eq/m^3)**
Raluy *et al.* (2006)	CML/Ecopoints 97/EI-99	SWRO - grid	45500	4	1.78
Raluy *et al.* (2005)	CML/Ecopoints 97/EI-99	SWRO -wind (150kW)	45500	4	0.17
		SWRO -wind (2MW)			0.117
		SWRO - PV Swiss (100 kWp)			0.9

		SWRO - PV Spain (100 kWp)			0.483
		SWRO - PV Swiss (100 kWp)			0.626
		SWRO - PV Spain (100 kWp)			0.347
		SWRO-hydropower			0.082
		SWRO - PV spain (100 kWp)			0.08
Munoz & Fernandez-Alba (2008)	CML	SWRO - grid	20000	4	1.9
		BWRO - grid		2	1.1
Wahidul K Biswas (2009)	IPCC 2007	SWRO-grid			3.896
		SWRO-wind			0.387
Zhou *et al.* (2011)	CML & TRACI	BWRO	10000	2	1.58
Jijakli *et al.* (2011)	EI-99	BWRO-PV	1.25		0.00167
Beery *et al.* (2012)	IPCC 2007	SWRO			2.26
Shahabi *et al.* (2012)	IPCC 2007	SWRO-grid	137000	3.5	4.61
		SWRO-wind			0.446
This study	IMPACT 2002+	SWRO-grid (100%)	4500	3	4.88
		SWRO-PV (100%)			1.935
		SWRO-wind (100%)			1.938
		SWRO-AD + grid (48%, 52%)			3.51

As for other impact categories, only the studies that present a complete list of the results were compared. The studies that use fossil fuels are summarized in table 18 and the ones that use RE are summarized in table 19. Significant differences are observed for many categories and this is attributed to the use of different units in calculating the impact, or for similar units, for the same reasons discussed above.

Table 18 Comparison of other impact categories to literature (fossil fuels)

Reference	Zhou et al (2011)		Munoz & Fernandez-Alba (2008)		**This study**
Method	CML	TRACI	CML		IMPACT 2002+
Plant type	BWRO		SWRO	BWRO	SWRO-grid
Capacity (m3/day)	10,000		20,000	20,000	4500
Electricity (kWh/m3)	2		4	2	3

Human toxicity	0.562	Carc: 0.00339	0.65	0.31	Carc: 0.02448
		Non-carc: 24.4			Non-carc: 0.0564
Respiratory effects		3.02E-03			0.00523
Photochemical oxidation	4.55E-04	3.04E-03	1.00E-03	5.50E-04	8.30E-04
Ozone layer depletion	4.30E-08	4.34E-08			2.00E-05
Ionizing radiation					81.6
Ecotoxicity	FW: 0.142	3.48			Aquatic:291.25
	Marine: 321				Terrestrial: 90.55
	Terrestrial: 0.00464				
Land use					0.045
Acidification	0.0116	0.564	0.027	0.015	Terrestrial: 0.103, Aquatic: 0.03391
Eutrophication	6.27E-06	7.66E-04			0.00108
Global warming	1.58	1.58	1.9	1.1	4.88
Energy use			42	23	75.64
Resource depletion					0.22

Table 19 Comparison of other impact categories to literature (RE)

Reference	Jijakli et al (2011)	**This study**
Method	EI-99	IMPACT 2002+
Plant type	PV-BWRO	SWRO-PV
Capacity (m3/day)	1.25	4500
Electricity (kWh/m3)		3
Human toxicity	Carc: 0.00112	Carc: 0.02448
		Non-carc: 0.05475
Respiratory effects	0.00889	0.00235
Photchemical oxidation	1.22E-05	3.53E-04
Ozone layer depletion	7.41E-07	2.00E-05
Ionizing radiation	3.12E-05	64.67
Ecotoxicity	1.87E+04	Aquatic:175
		Terrestrial: 53.45
Land use	69.5	0.06742
Acidification	158	Terrestrial:0.03178, Aquatic: 0.01034
Eutrophication	158	0.00091
Global warming	0.00167	1.935
Energy use	1.36E+04	35.477
Resource depletion	5600	0.22

Among the limitations that the forms of RE employed in this study have been subject to is that continuous operation could not be achieved in any of the forms. For AD, the maximum attainable percent was 48% due to amount of waste collected and transformed, whereby increasing the amount of waste could yield higher quantities of biogas. However, increasing the capacity of the AD unit is limited by the lack of maturity of this process on an industrial scale and the increase in energy input for the process itself with increase of waste quantities. Additionally, the design in this study does not make use of the produced energy to feed the process itself, whereby external sources (i.e. grid) were required to fulfill the heating requirements of the AD process. For PV, the maximum attainable percent for grid-connected systems was 48% mainly because of intermittency issues where the sun is not only not shining at night, but also during daytime there may be cloudy or rainy weather. Also, for this study, averaged solar data for all of Lebanon was used because no data was found specific for the chosen town. This also serves as a limitation as it provides more general conclusions rather than site specific ones. An additional critical limitation is the massive land requirement for the PV panels as the installation was selected to be land mounted. For wind, maximum renewable percent was 70% for on-grid systems and limitations also included intermittency due to weather conditions especially considering that the wind plant was built onshore where wind is constantly fluctuating so a continuous flow of power cannot be achieved.

Regarding the results, some limitations were also identified and are listed below:

- Does not account for economic and social implications for each of the RE forms and SWRO plant. Initial investment costs, operating costs and impact on nearby communities (noise, construction etc.) should be considered as an essential aspect in deciding on the best alternative to adopt.
- Lack of reliable data for some units and for most processes in Lebanon, which led to the use of assumptions. Due to confidentiality reasons, not much information could

be collected regarding the production of unit processes especially the ones used in the SWRO plant which led to approximations and lack of detail.

- The LCIA method used is global, and though it could be applied reliably in this study, it could be more accurate to develop a method that takes the local context into account.
- The current LCI for the processes represents temporal information of the emissions, when actually pollutants released do not have the same impact across the entire lifetime especially for electricity due to improvement of technologies.
- The system boundaries do not include the impact of water distribution.

Despite the limitations addressed, this project provides an innovative integration not previously tackled in the literature. No study has addressed the LCA of the combination of AD with desalination as a viable solution to two of the main issues faced by Lebanese societies: water shortage and waste disposal. Additionally, it adopts a comprehensive approach tackling most midpoint categories including the impact of land use which has not been previously considered in the literature. It also studies several RE alternatives with SWRO using a combination of three different software programs, which highlights the novelty and realistic representation of this work. Data collection takes into account the local context such that the study tackles the Lebanese case in specific, thus providing more pragmatic results that could have substantial and practical impact in the future and new ground for additional research and progress.

To deal with some of the limitations considered and further improve the results obtained, future work and recommendations could include:

- Performing cost analysis to determine at least approximate values for investment costs, operating costs and return on investment because despite the importance of environmental considerations, economics is an essential part of any project and affects the decision-making process.

- Designing a system that integrates all three forms of RE or at least two of them optimally and determining whether it could provide more notable results environmentally and economically. This type of system could make use of one form of RE to make up for the limitations of another.
- To further improve the RE systems:
  - ➔ The AD process could be tacked in two ways: increasing the amount of waste transformed by collecting waste from nearby towns (taking transportation requirements into account) instead of relying solely on the town under study so that amount of biogas generated could increase and in its turn decrease reliance on fossil fuels. Secondly, it is a very important solution to design a heat and power co-generation system instead of implementing a conventional generator as was the case in this study to make use of the waste heat and thus increase process efficiency. Additionally, the heat and electricity generated should be used to satisfy the energy requirements of the process itself instead of relying on external sources.
  - ➔ As for the wind and PV systems, it is recommended to optimize construction locations by performing additional statistical and forecasting studies on solar and wind resources in selected sites, so that better efficiencies could be achieved and thus higher renewable fractions.
- To further improve the SWRO system:
  - ➔ The impact of replacing HCl with H_2SO_4 should be looked into as a viable option for further decreasing the impact in the operation phase.

  - ➔ It should be determined whether applying economies of scale would yield improvements in the results. Examples include combining activated carbon and multimedia into one filter since both units had a high impact in many categories.
  - ➔ The impact of subsurface intake instead of open intake for seawater extraction should be determined.

- To further improve both RE and SWRO systems:
  - ➔ The impact of using alternative materials of construction should be determined since the most used materials in all systems being steel, copper and cast iron had significant impacts in most units, while taking construction cost into account.
  - ➔ It should be determined whether applying economies of scale by reducing amount of materials used such as fewer number of filters, panels and turbines will yield reductions in environmental impact.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

The main objective of this work was to use the LCA tool to quantify the environmental impact of a designed SWRO plant and compare the impact reductions that can be achieved when using PV, wind and AD (each separately) to power the plant instead of the Lebanese electricity grid. This study has succeeded in proving that significant reductions can be obtained when switching to any of the studied RE technologies instead of conventional fossil fuels. The main conclusions that were drawn from this work are listed below.

- Among the 3 technologies compared, wind energy proved to be the most successful for the case of Lebanon, especially for remote locations such as the one chosen, which benefits from high wind speeds.
- Overall, increase of renewable fraction resulted in impact reductions in all categories except for land occupation and mineral extraction (for wind and AD) and only land occupation for PV, in which increases were observed.
- For all scenarios, operation was the main contributor in all impact categories except for ozone layer depletion in which construction had a higher load mainly caused by membrane production. Otherwise, construction materials had a low weight in all categories.
- In all categories, impact in the operation phase is caused by chemical use and electricity consumption. For some categories, HCl is much more impactful than electricity making the reductions when switching to any form of RE very minor.
- Electricity from PV has 0 impact in all categories because the maintenance work is very minimal and periodic cleaning of the PV panels is done only with tap

water. Electricity from wind has very minimal impact (1-2% in most categories) due to the use of lubricating oil for maintenance and sulfur hexafluoride in transforming the electricity from high to low voltage. Electricity from biogas has an impact in many categories because of the emissions resulting from burning the gas in a generator and the transformation from high to low voltage. However, the impact remains lower than that obtained from the grid.

- Units that had the highest contribution in SWRO plant construction were mainly membrane production, activated carbon and multimedia filters and for some categories, tanks and civil works.
- Construction of the RE plants adds an impact in all categories. For PV plant construction, materials that were most prominent in increasing the load were PV panels, mounting system and batteries (for off-grid scenarios) whereby in some categories, they contributed in increasing the overall load more than that obtained with the grid. For wind plant construction, wind turbine construction and batteries increased the load and contributed more than the network connection. For biogas plant construction, the generator itself had the biggest contribution in increasing the load in most categories and within the AD unit, materials such as cast iron, copper and reinforcing steel had the highest impact.
- Disposal has 0% contribution to the impact, despite using 100% land fill which is considered the worst-case scenario as many materials can be recycled or reused.

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