

Potential Reduction of Carbon Burden for Senak Seawater Desalination Plant in Malaysia

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Abstract

Purpose

Carbon footprint calculation is one of the approaches available in the Life Cycle Assessment (LCA) system, which can be considered as a decision support tool for environmental sustainability management. Hence, this purpose of this study is to examine the potential contribution of the product, namely water through carbon footprint measurement. Seawater has been selected as the source for clean water transformation in Senak due to its ability to meet the growing demands of the local population and its ability to be recycled in the long term.

Methods

In this study, carbon footprint assessment was used to investigate seawater production systems from a desalination plant in Senok, Kelantan, Malaysia. Three stages of the desalination plant processing system have been investigated and the inventory database has been developed using the relevant model framework. The LCA method, in accordance with ISO14040-43 guidelines has been simplified with working unit selected is 1 per cubic meter of treated water produced from a salt water desalination source.

Results and discussion

Overall, the results of the study indicate that the Revolutionary Osmotic (RO) technology that has been used in the desalination plant in the study area is one of the best options to meet the demands of the environmental sustainability agenda (SDGs). This is due to a lower carbon dioxide (CO₂) emission of about 3.5×10^{-2} kg of CO₂ eq per m³/year that has been recorded for the entire operation of the system. The other pollutants involved the emission of NO_x and Sox, which were considered to be insignificant. However, if the plant continues to operate completely on fossil fuel for the next 25 years, the emission is expected to affect the health of the community.

Conclusions

Several factors that influence important errors in carbon footprint decisions such as the lack of EIA reporting data and the literature on carbon footprint in the Malaysian scenario. The total dependency of electrical source for SWRO process of fossil fuel is the most critical factor in the carbon footprint issue in this study. These findings can be used to develop a carbon footprint model that can commercialise carbon tax, carbon economy capital, energy security assurance, and standard carbon regulation and legislation in the context of local desalination projects.

The Informative

- The Revolutionary Osmotic (RO) technology is one of the best options to meet the demands of the environmental sustainability agenda (SDGs).
- The carbon footprint model that can commercialise carbon tax, carbon economy capital, energy security assurance, and standard carbon regulation and legislation in the context of local desalination projects.
- The lack of EIA reporting data and the literature on carbon footprint in the Malaysian desalination scenario need to be identified in more detail in future research.

1. Introduction

Advances in technology have led scientists, academics, engineers, and architects to compete and innovate on every aspect of the desalination management system, ultimately resulting in the balance of the earth's transition to global peace (Masaru and Hiromu, 2018; Abdullah et al. 2019). Currently, the best choice for a desalination plant system is to use Reverse Osmosis technology (RO), rather than electro dialysis, microfiltration (MF), ultrafiltration (UF) technologies. The development of innovations in the use of RO system has intensified with proven integration success using SWRO membrane with a low pressure, two-stage high recovery SWRO system with a low pressure, and also the SWRO-PRO hybrid system (Lattemann and Höpner, 2008; Kurihara and Takeuchi, 2018). Many research have been conducted to investigate the feasibility of applying Reverse Osmosis technology using brackish water, river water, and drinking water and groundwater sources. However, despite the robustness of technology and systems, the emission of material output remains a potential impact and threat to the deterioration of the environment.

The main challenges in the RO process for desalination systems are (1) high energy consumption, (2) high cost of technology installation and (3) the use of chemicals. Aspects 1 and 2 are critical in maintaining environmental balance, particularly concerning climate change issues and ozone depletion. Therefore, the lack of consistent research data on SWRO systems in the Malaysian context has deterred the policymakers from supporting the recovery of challenges 1, 2 and 3. Although the reverse osmosis membrane system is the best technology option at present, its weakness is clearly attributed to the inefficiency of water production (Shresthal, 2011). A study by Griffiths and Wilson (2009) have found that carbon footprint has contributed to the US water production sector, accounting for 5% of all carbon emissions. Optimisation of the best RO methods are improved membrane technology (low permeable membrane or composite fouling), high pressure pump selection, and renewable energy use (Kesieme et al. 2013; Jungbin et al. 2019).

Another important aspect that can be attributed to the SWRO challenge is the use of electricity that could potentially affect the depletion of the ozone layer, water pollution and imbalance in carbon dioxide gas and natural resources. In the 2000s, the Carbon Footprint (CF) method based on LCA-carbon footprint approach (ISO 14067, 2013) has been widely used to measure the CO₂ equivalent emissions, which is based on the current contributions from the SWRO project. The use of the CF indicator enables decision-

makers to determine the location of hot spots by drawing up austerity measures and the reduction of natural carbon emission to the environment. Therefore, these CF indicators are suitable for use in driving sustainable desalination projects. The findings of a social carbon cost assessment have concluded that a 54% reduction in desalination costs is equivalent to USD150 to USD200 per tonne of carbon dioxide (Roibás et al. 2018). Although the desalination case-based carbon footprint method has been widely used for the study of social carbon costs and carbon emissions, it still has some limitations to motivate its research in the local context.

Carbon footprint assessment needs to be studied solely from the overall life cycle assessment process to overcome this problem. In general, the benefits of providing raw carbon inventory data for cases of desalination can impact the development of the carbon policy and regulations in Malaysia. Carbon footprint indicators can estimate carbon emissions from different aspects of the scenario and systems for a given process or product, and thus help decision-makers overcome these limitations and challenges. The achievement of carbon footprint research in Malaysia can be considered to be in line with those in other Southeast Asian countries such as Singapore, Thailand, Indonesia and several other countries (Lew et al. 2017; Jung wan Lee, 2019). However, the focus of carbon footprint research on the forestry, agriculture, municipal, transportation, and construction sectors is growing compared to that on the water resource management sector. Thus, in line with the demands of the Green Technology Master Plan Malaysia 2017-2030, which is undertaken under the Green Technology and Climate Change Council Malaysia (KeTTHA), the carbon footprint approach has been used as the preferred method for the case of the Senak desalination plant. Undoubtedly, the partnership between Tenaga Nasional Bhd (TNB's) subsidiary Renewables Sdn. Bhd. and the Energy Commission and SEDA to adopt the Energy Tariff and Net metering system is a great solution if the results of this carbon footprint can be presented to the relevant decision-makers.

Despite massive academic and local authorities' efforts towards the development of the latest technological desalination projects, the RO membrane performance has been performing as desired. Recent studies have shown that the life cycle assessment using the carbon footprint index is a critical consideration and energy saving is particularly needed to maximise membrane performance, diameter operation and water feed (Qasim et al. 2019). The researchers suggest that a comprehensive review of the hybrid membranes, entropy concentration and thermodynamic reduction has the great potential to improve energy-saving and resource recovery, and additional studies are needed to control the effect of climate change. This study examines the potential contribution of the product, namely water through carbon footprint measurement. Seawater has been selected as the source for clean water transformation in Senak due to its ability to meet the growing demands of the local population and its ability to be recycled in the long term. The main objectives of this paper are to (1) review current flows of GHG emissions and carbon footprints in this SWRO system and (2) to evaluate CF performance in the SWRO system, thus proposing some long-term suggestions on the issue of carbon savings.

2. Materials And Methods

2.1. Initial Analysis

In order to obtain accurate data on carbon footprint, inventory-based questionnaires have been developed and sent to SWRO plant maintenance personnel, and to several stakeholders such as contractor developers, site managers, engineers, village heads and other individuals who are directly involved in Kampung Senak, Kelantan. Among the information that is acceptable, only complete and analytical, numerical and empirical data are available, including some validated and accepted laboratory test results. The LCA method, in accordance with ISO14040-43 guidelines (ISO, 2006a, 2006b), has been simplified: first, goal setting and scope. The working unit selected is 1 per cubic meter of treated water produced from a salt water desalination source. Second, the development of the content of inventory data in which the mining of material input data output is presented as an LCI chart. Third, life cycle impact assessment (LCIA) using Simapro 8.5 software has been performed on a single inventory spreadsheet. The last is, the presentation of decisions by implementing data interpretation. Figure 1 shows the system of study boundaries involving the extraction, treatment and preparation of desalinated water. This study excludes carbon emissions from decorative materials because of data that are related to poor usability.

2.2. Data Inventory

The inventory database for the construction and operation phases is arranged and presented in a spreadsheet in Table 2. Most of the input and output data involving energy, raw materials, water and gas for certain operations were collected and quantified from the local data sources from the Senak desalination plant engineer, administrators of Bachok district and the remaining data were from Ecoinvent, Simapro (Pre Consultants, 2018). All the information that is related to the civil engineering structures of SWRO desalination plant in the 'blue book' is not made public and should be kept confidential following the requirements of the Ministry. However, the overall gross estimation of raw materials in the construction phase is shown in Table 1. The recycling of materials has not been considered in this study for the dismantling phase involving the transportation and disposal of waste materials at the disposal area. This is because the plant has been in operation for less than two years and due to the frequency of shut down for maintenance. This SWRO plant is also assumed to have a life span of 25 years with less than 5 years of membrane lifetime.

Table 1 The gross estimation of raw materials in the construction phase

	Material Description
Site preparation (including division work)	Backhoe, lorry, laborer
Office site	Cabin, footing and poles, cold form truss, metal deck
Store and toilet	Footing, poles, Ground beams, roof beams, concrete slabs, ceramics, Paint, windows, inlet pipes, doors, hoses, basins, taps, asbestos ceilings, plaster, brick wall, BRC, R10, FWK, Polythene sheet, render, toilet bowl , mirrors, sewage tanks, asbestos ceilings and so on.
House for seawater desalination plant	Footing F1, F2, column stump C1, concrete floor, expansion joint, rooftop, 1 column
Pump house	Concrete floor, steel frame, roof, lock
Water tank	Hardcore, concrete, BRC, cement, FWK, PE tank, accessories
Distribution pipeline	Concrete floors, brick walls, plaster, tap
Entrance road	Sand, CR300 mm, binder, wearing
Surface drainage system	Drain, sump
Plumbing system	HDPE, water intake to salt water tanks, concrete blocks etc.

Table 2 The spreadsheet of inventory data of 1 m³ of desalinated water production

Inputs	Calculated Value	Unit	Source
Materials/fuels			
Reinforcing steel	3.96E-04	kg/m ³	Calculation
Polyethylene	1.75E-03	kg/m ³	Calculation
Chromium steel pipe	1.90E-04	kg/m ³	Calculation
Concrete, 30-32MPa	2.79E-05	kg/m ³	Calculation
Steel	2.76E-05	kg/m ³	Calculation
Nylon	1.41E-03	kg/m ³	Calculation
Polypropylene resin	1.96E-03	kg/m ³	Calculation
Electricity			
Pumping seawater	3.00E-01	kWh/m ³	Calculation
Pre-treatment	1.50E-01	kWh/m ³	Calculation
Reverse Omosis	2.40E+00	kWh/m ³	Calculation
Wastewater	2.50E-01	kWh/m ³	Calculation
Post-treatment	1.70E-01	kWh/m ³	Calculation
Storing+distribution	1.00E-01	kWh/m ³	Calculation
Chemicals products			
Polyaluminium chloride	2.70E-03	kg/m ³	Ecoinvent 3
Polyacrylamide	1.80E-03	kg/m ³	Ecoinvent 3
Soda ash	1.50E-01	kg/m ³	Ecoinvent 3
Hydrochloric acid	4.50E-03	kg/m ³	Ecoinvent 3
Sodium hydroxide	5.40E-03	kg/m ³	Ecoinvent 3
Chlorine	1.00E-03	kg/m ³	Ecoinvent 3
Sodium hydrogen sulphite	1.08E-02	kg/m ³	Ecoinvent 3
Sodium hypochlorite	5.40E-03	kg/m ³	Ecoinvent 3
Calcium carbonate	5.40E-03	kg/m ³	Ecoinvent 3

2.3. Calculation of GHG Emission

Estimation of the potential GHG emission adopts the IPCC 2013 approach, which is the global warming potential (GWP) throughout 100 years (IPCC, 2006). Table 3 shows the sustainability composition values for a RO desalination plant with local electrical energy sources. The basic solution to calculate the CO₂ equivalent emission factor and carbon footprint is by using Equations 1 and 2 with the values of 1, 21, and 310 for GWP multipliers (Jiahong Liu et al. 2015; Fahad et al. 2018). However, this study did not consider the embodied energy and embodied GHG emissions.

$$\text{Emission Factor (kgCO}_2\text{eq/kWh)} = 1*(\text{kgCO}_2\text{/kWh}) + 21*(\text{kgCH}_4\text{/kWh}) + 310*(\text{kgNO}_2\text{/kWh}) \quad (1)$$

$$\text{CFP (kgCO}_2\text{eq/m}^3) = \frac{\text{CO}_2\text{eq (kg/kWh)} * \text{Electricity Utility (kWh/yr)}}{\text{Water Produced (m}^3\text{/yr)}} \quad (2)$$

Table 3: Sustainability composition of RO plant with local power source

Environmental indicator for CO ₂ Kg CO ₂ /m ³	6
Environmental indicator for SO ₂ , Kg SO ₂ /m ³	0.005
Environmental indicator for NO _x Kg NO _x /m ³	0.009
Fuel resource indicator, Kg fuel /m ³	1.8

3. Results And Discussion

3.1 CO₂-eq Emissions in the Construction Process

Senak desalination plant can be considered to be at its infancy stage, having been operated for only two years. It is hard to determine the indirect release of carbon footprint during its early phases of construction due to reliability issues of the initial raw data, such as utilities which include electrical and water consumption and human resources, piling/ground work, land clearing, energy recovery devices, filters and membrane, pumps and others. Therefore, only six compartments were investigated in this study. Figure 2 shows the use of concrete building materials contributing the most to greenhouse gas (GHG) emission at 8.48×10^{-5} kg CO₂-eq, followed by polyethylene and trucks at 3.51×10^{-5} and 6.19×10^{-6} kg CO₂-eq, respectively. The total GHG emission was 1.46×10^{-4} kg CO₂-eq which contributed 55% to this phase. Several important steps can be implemented in the future to reduce the GHG emission by requiring specific reporting such as environmental impact assessment (EIA). However, in this study, the EIA report was not necessary due to the small plant scale (DOE, 2019). In terms of materials, the cost-saving factor in the procurement of certain raw materials can also reduce the carbon footprint (Jani, 2016). Also, the introduction of incentive policy of Renewable Energy Power Purchase Agreements under the FiT: Feed-in-Tariff and “MyPower” mechanism by KeTTHA and TNB towards SWRO Senak plant should be reviewed in terms of feasibility.

3.2 CO₂-eq emissions in the Operation process

The five phases of the evaluated SWRO process are seawater pumping and intake, pretreatment, reverse osmosis operation, post treatment and water storage and distribution. Figure 3 shows the total carbon footprint of 3.5×10^{-2} kg CO₂-eq/year, with the assumption that the contribution was not significant and way smaller than the reported values of 1.599–5.63 kg CO₂-eq for Spain, 2.208–7.46 kg CO₂-eq for Israel, 2.562 kg CO₂-eq for China, and 2.1–3.6 kg CO₂-eq for Singapore (Pablo et al. 2014; Jiahong Liu et al. 2015; Biswas et al. 2016; Xuexiu Jia et al. 2019). The other contributing factors are plant capacity, adaptation of technology, fuel type, and the selection of attribute calculation in scopes 1, 2, and 3. In this

study, the three dominant phases contributing to carbon footprint were reverse osmosis operation with 75% (2.6×10^{-2} kg CO₂-eq per m³), seawater intake with 12% (3.2×10^{-3} kg CO₂-eq per m³) and post-treatment (2.5×10^{-3} kg CO₂-eq per m³). The intensive application of 100% fossil fuel to generate electricity for SWRO plant was identified as the major factor in the increase of carbon and GHG emission, as shown in Figure 4. The results also show a strong correlation ($R^2 = 0.89$) between the value of energy consumption and the carbon emission based on the evaluated process phase. Notably, a further study is needed for the phases of manufacturing, transportation, and membrane because the GHG emission from the said phases complements the results of the carbon footprint for SWRO system. The current research of the new capacity of SWRO operation, which has not been fully functional and is less than one-year in operation could be the contributing factors of the low relative carbon footprint.

Based on the percentage contribution between chemicals and electricity in figure 5, the results are in agreement with those that have been reported in Sydney water (2004), Biswas (2009), Cooley and Heberger (2013), and Shahabi et al. (2014). The utility of electricity consumption was 3.613 kg CO₂-eq, which was determined using the IPCC GWP 100 analysis, as shown in Figure 3. Meanwhile, the utility of chemicals consisting of Polyaluminium chloride, Polyacrylamide, Soda ash, Hydrochloric acid, Sodium hydroxide, Chlorine, Sodium hydrogen sulfite, Sodium hypochlorite and Calcium carbonate contributed a total of 0.146 kg CO₂-eq (4%). According to Gobin et al. (2019), the quantity of chemicals will be higher when the productivity of potable water production is higher. For example, the use of lime, fluoride, and carbon dioxide to reduce water hardness and produce good quality water can contribute to the carbon footprint. Besides, the potential of carbon footprint occurred during the use of chemicals for removing impurities in the stage of freezing and sedimentation, with the need for an embodied energy of 22%. Based on Figure 5, the change in electrical utility is significant at 96%, which is equivalent to 2.8 kWh/m³ for water pumping, membrane operation, and water distribution to main pipes. Based on the work by Raluy et al. (2005), Stokes and Orvath (2009) and Elimelech and Philip (2011), several best recovery steps for electricity are by installing energy recovery device and optimising the pump use and membrane permeability. Fahad et al. (2018) have proven that the use of a membrane is also possible to reduce carbon footprint by increasing the diameter of the membrane during the high rejection of boron, bromide, and other relevant materials.

As mentioned earlier, this SWRO Senak pilot plant project was developed on a small scale with a capacity of 500 m³ per day to cover a 3000 household population. The overall carbon emission from the plant was small and gave an insignificant impact on the environment, as shown in Figure 6. The CO₂ emission was the highest contributor with 3.48×10^{-3} kg CO₂-eq, followed by methane with 2.70×10^{-4} kg CO₂-eq. The other pollutants involved the emission of NO_x and So_x, which were considered to be insignificant. However, if the plant continues to operate completely on fossil fuel for the next 25 years, the emission is expected to affect the health of the community. As a conclusion, the control of GHG emission can meet the agenda of the Kyoto Protocol for global climate change mitigation.

3.3. Relationship between limitations, strategies and adaptation

In the context of desalination research in Malaysia, carbon footprint indicators still require various innovations, especially in the preparation of the LCIA literature that is easier to understand in the actual local real scenario. For example, the difficulty in obtaining an accurate estimate of the factor of an actual mix energy emission in Malaysia affects the carbon footprint reporting and delay the transition process of the use of renewable energy. The study of the scopes of carbon footprint also requires a comparison between the sources of groundwater, brackish water, wastewater and treated water that is given that the community around Senak highly depends on the feed water sources. Data loss and lack of information that are related to materials disposal, construction of plant infrastructure, tanks and transportation services are the most difficult issue to model the indirect carbon footprint emission. According to Gobin et al. (2019), limited data accessibility such as chemicals and energy via data extraction using different models such as GaBi, West is the major limitation in the research of carbon footprint desalination in Cape Town, Africa. Therefore, further research needs to be done with the involvement of sensitivity analysis towards the construction, operation and dismantling phases. Several major categories of uncertainty that contribute to accuracy in the results of carbon footprint calculation are data uncertainty, model uncertainty, epistemological uncertainty, estimation uncertainty and option uncertainty (ISO 14043, 2000). Several important inputs to consider for uncertainty in the carbon footprint are raw materials (steel and cement), feed water volume, energy consumption, GHG emission distance measurement, and Bachok clean water credit issue.

Since the CF system boundary evaluated was small, the carbon footprint calculation was focused on the direct estimation rather than indirect, such as the exception of several downstream, upstream, product and process systems. Therefore, the overview of the environmental impact performance was not well presented. In addition, the CF results can be meaningful if this approach is integrated with other indicators and attributes such as energy and water. Also, several carbon footprint evaluation instruments such as WESTWeb model, CHEApet, Simulation Platform No.2 (BSM2G), Johnston tools, LCA hybrid tools and other equipment can estimate more accurately (Pablo et al. 2014). As mentioned earlier, SWRO sustainability is related to the alternative selection to minimise environmental impact, and the integration between the different sources of energy with a renewable energy was fundamentally selected to meet the objective. In other literature reviews, the energy reduction via membrane technology increases up to 38% with the integration of the hybridised SWRO and other renewable energies (Biswas et al. 2016). The replacement of fossil fuel in a current desalination process is expected to reduce the cost of clean water production in Senak as well.

Previous studies have reported a similar finding in terms of CF impact which shows an inverse correlation between conventional desalination system versus desalination and carbon emission (Alon, 2018). There are also studies which have reported that the introduction of a dummy process via integration of Conventional Electrodialysis (ED) or and Bipolar Membrane Electrodialysis (EDBM) has successfully reduced the GHG emission to zero (Karel et al. 2013). Therefore, the trend changes in the carbon footprint profile and the environmental load recovery performance is expected to occur frequently because carbon emission from the desalination sector affects the current global climate change. Based on this study, a further study is proposed to detail the low carbon development policy by compiling novel process

outcomes, inventory and LCA effect category. This future study will provide a better understanding for the policymaker at the national and local level.

4. Conclusion

The sources and impacts of hotspot and non-hotspot from GHG and CO₂ emission for the performance of small scale SWRO in Senak were investigated in the carbon footprint mode. Several conclusions can be made from this study:

- The total dependency of electrical source for SWRO process of fossil fuel is the most critical factor in the carbon footprint issue in this study. However, the GHG emission from SWRO plant (3.5×10^{-2} kg CO₂-eq/yr) is 30 and 39-fold deficit compared to that of the desalination treatment plant in Carnoneras, Spain and Australia (Biswas, 2009). This value was affected by minimum chemicals, the performance of new membrane technology, small plant capacity, land area, water feed and intermittent operating duration.
- The option of renewable energy and integrated desalination system (state of the art desalination technologies) could reduce the GHG emission to 90% (based on the findings of Shahabi et al. 2014) which is equivalent to 1.09×10^{-1} kg CO₂-eq/year for this SWRO plant.
- These findings can be used to develop a carbon footprint model that can commercialise carbon tax, carbon economy capital, energy security assurance, and standard carbon regulation and legislation in the context of local desalination projects. However, a further study on the financial investment factor towards new desalination technology adaptation is critical and necessary.

Abbreviations

CO₂-eq/year: Carbon dioxide equivalent per year; CF: Carbon Footprint; GHG: Greenhouse Gas Emission; ISO: the International Organization for Standardization; LCA: Life Cycle Assessment; SWRO: Senak Seawater Reverse Osmosis Plant;

Declarations

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Authors' contributions

The theoretical framework, research design, data analysis, and inferences drawn was solely carried out by the author LS. The author(s) read and approved the final manuscript.

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Availability of data and materials

The data used for this research will be made available upon request. Also the data is available on relevant authorities' webpages.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Figures

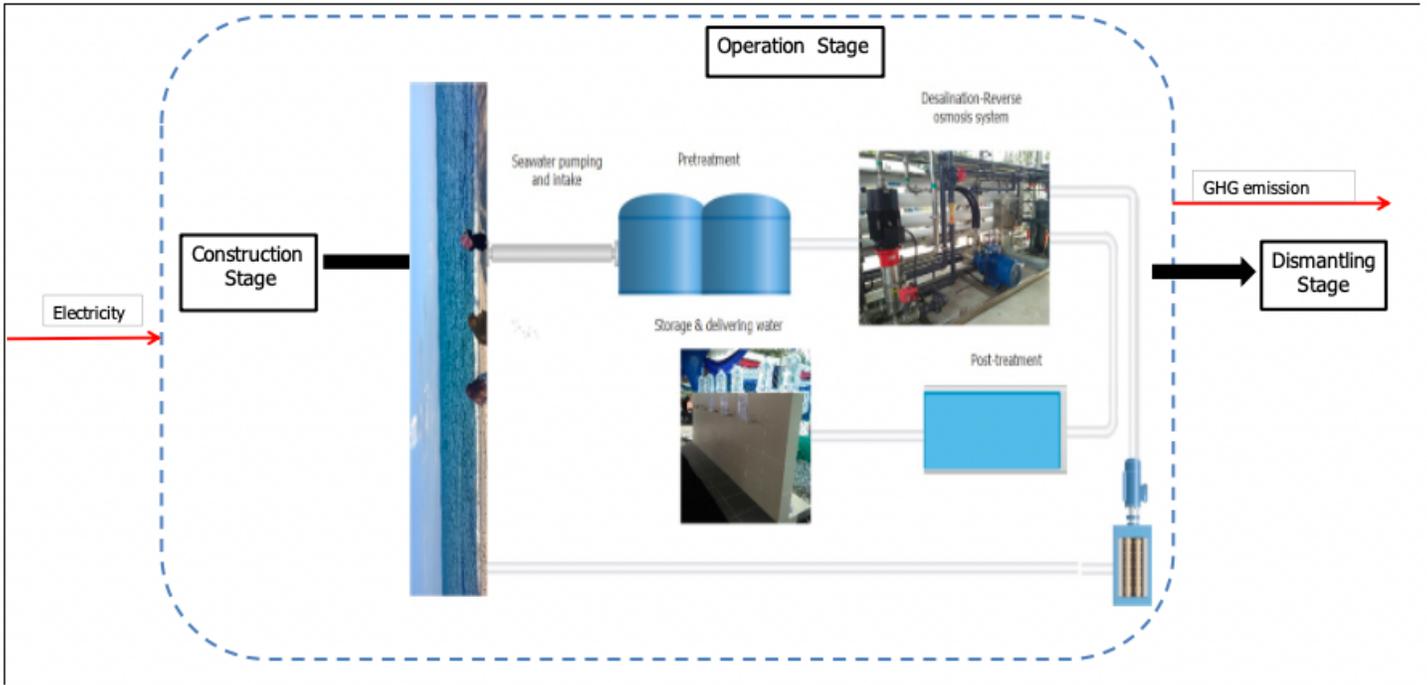


Figure 1

Conceptual images for seawater desalination system boundaries in Senak. The blue dotted point line indicates the boundary of the scope of the study.

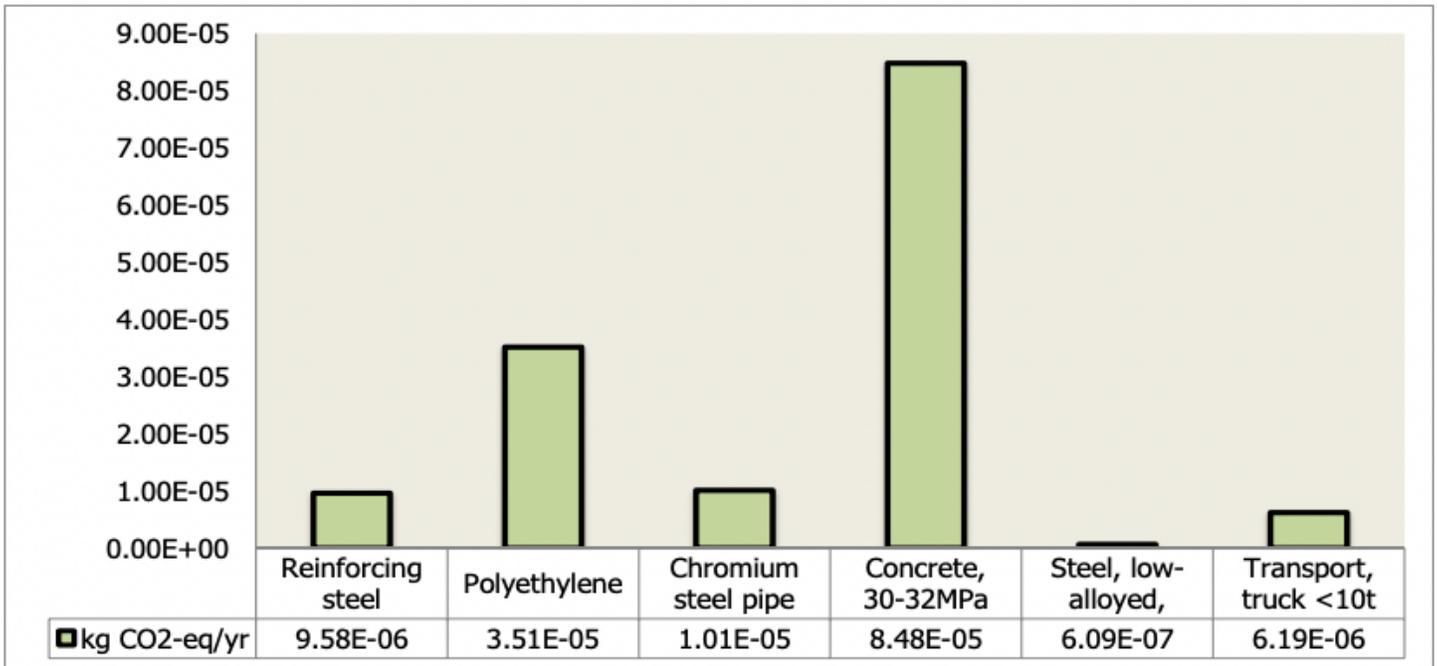


Figure 2

GHG emission for the Senak SWRO desalination construction stage

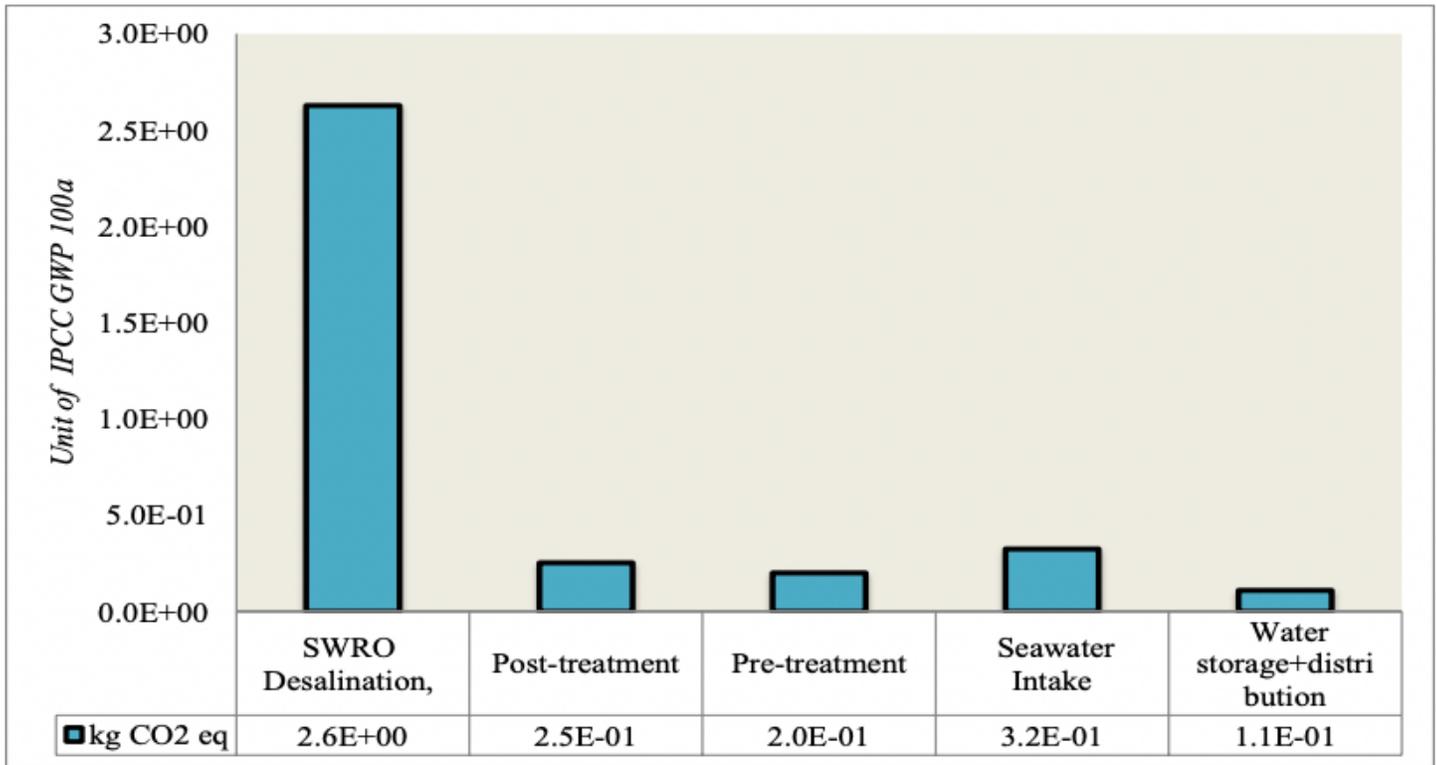


Figure 3

Contribution of relative carbon footprint, according to phase of process by SWRO in the operation stage.

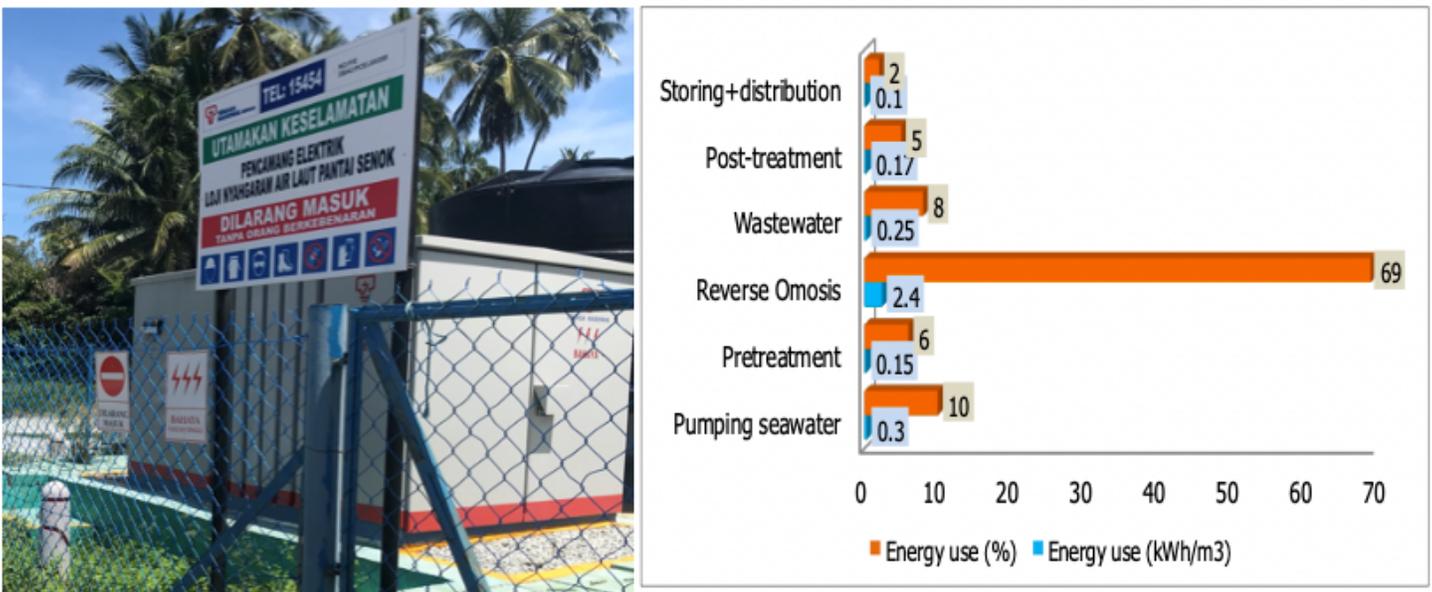


Figure 4

TNB's electric power generating system covers the transmission and distribution of electricity, according to the SWRO process stage in Senak, Kelantan.

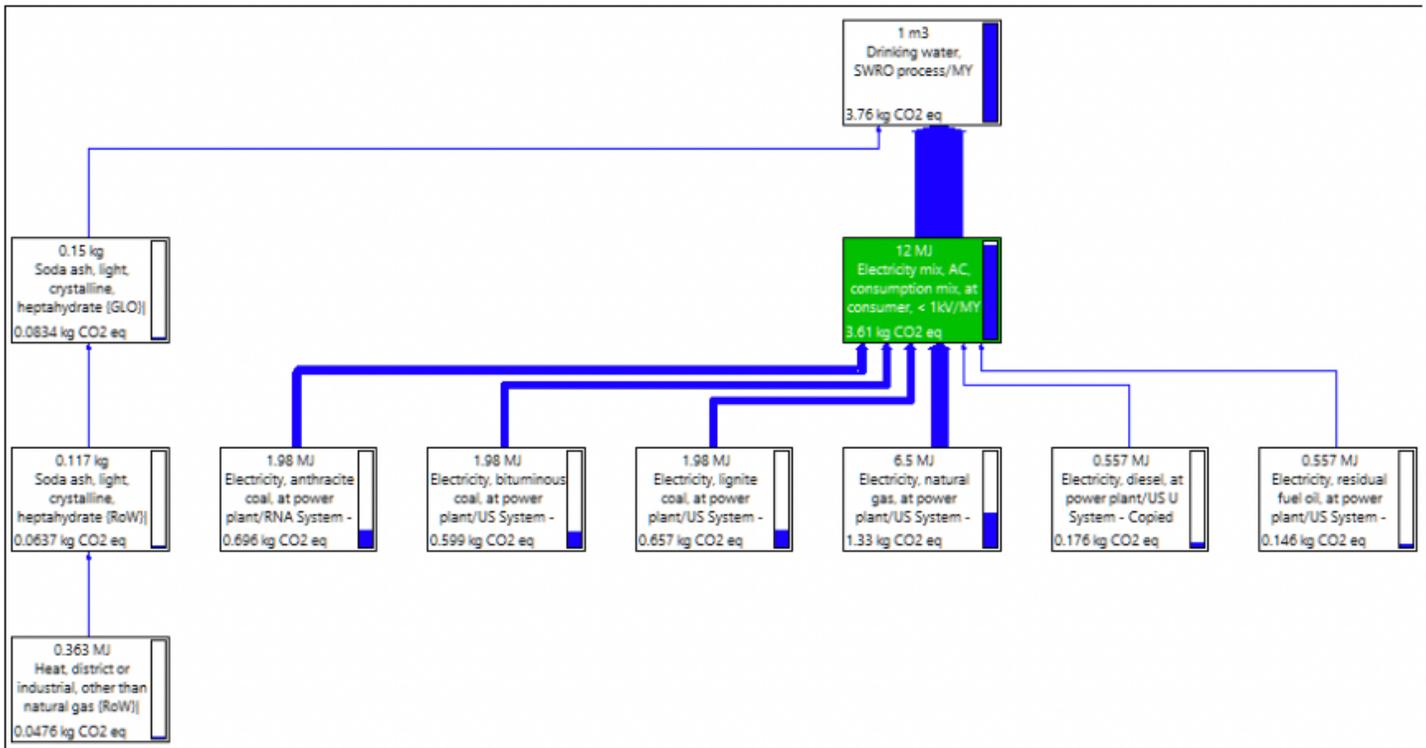


Figure 5

Dendrogram of the main contributions to GHG emissions per cubic meter of SWRO from chemicals (4%) and electricity (96%) factor.

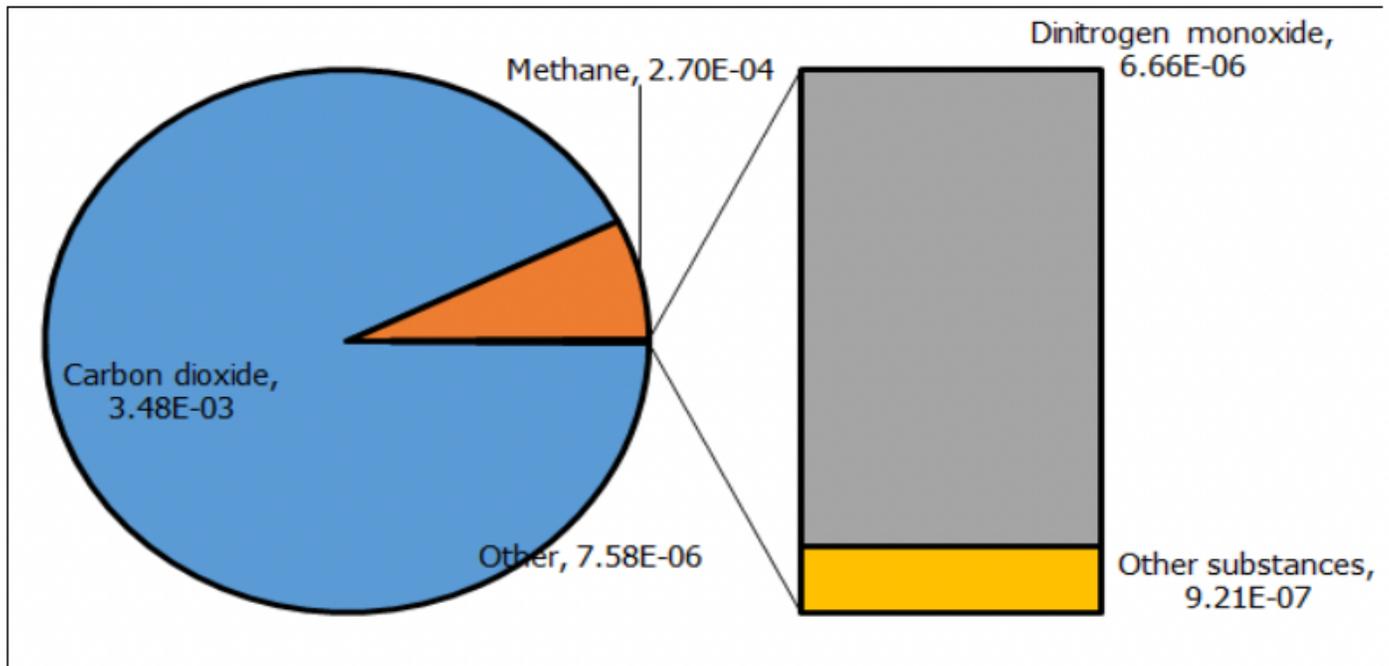


Figure 6

The relevant airborne (substance) emissions produced in kg CO₂eq per 100 year by the whole process of SWRO in Senak.