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Carbon Footprint-Energy Detection for Desalination Small Plant Adaptation Response

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Abstract: The Life Cycle Assessment (LCA) system, which can be used as a decision support tool for managing environmental sustainability, includes carbon footprint assessment as one of the available methodologies. In this study, a carbon footprint assessment was used to investigate seawater production systems of a desalination plant in Senok, Kelantan, Malaysia. Three stages of the desalination plant processing system were investigated and the inventory database was developed using the relevant model framework. Subsequently, measurements and interpretations were performed on several key indicators such as greenhouse gases, energy efficiency, acidic gases, smog, and toxic gases. Overall, the results of the study indicate that the Reverse Osmosis (RO) technology that is 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 the lower carbon dioxide (CO_2) emission, of about 3.5×10^{-2} kg of CO_2 eq per m^3/year, that was recorded for the entire operation of the system. However, 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, in addition to direct and indirect carbon input calculations, need to be identified in more detail in future research.

Keywords: desalination; carbon footprint; Life Cycle Assessment (LCA); seawater; energy

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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 [1,2]. Currently, the best choice for a desalination plant system is to use Reverse Osmosis technology (RO), rather than electrodialysis, microfiltration (MF), ultrafiltration (UF) technologies. The development of innovations in the use of the RO system has intensified with the proven integration success using a SWRO membrane with low pressure, a two-stage high recovery SWRO system with low pressure, and the SWRO-PRO hybrid system [3,4]. A large amount of research has been conducted to investigate the feasibility of applying Reverse Osmosis technology using brackish water, river water, drinking water, and groundwater sources. However, despite the robustness of the technology and systems, the emission of material output has a potential impact and remains a 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 policymakers from supporting the efforts to overcome 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 [5]. A study by Griffiths and Wilson [6] found that the US water production sector has contributed to the carbon footprint, and accounts for 5% of all carbon emissions. Optimization of the best RO methods is achieved via improved membrane technology (low permeable membrane or composite fouling), high pressure pump selection, and renewable energy use [7–9].

Another important aspect that can be attributed to the SWRO challenge is the use of electricity, which can potentially affect the depletion of the ozone layer, water pollution, and an imbalance in carbon dioxide gas and natural resources. In the 2000s, the Carbon Footprint (CF) method based on the LCA-carbon footprint approach [10] was widely used to measure the CO_2 equivalent emissions, and 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 implementing austerity measures and steps to reduce the natural carbon emissions to the environment. Therefore, these CF indicators are suitable for use in driving sustainable desalination projects. The findings of a social carbon cost assessment concluded that a 54% reduction in desalination costs is equivalent to USD 150 to 200 per tonne of carbon dioxide [11]. Although the desalination-based carbon footprint method has been widely used for the study of social carbon costs and carbon emissions, it still has some limitations when applied to 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 be used to 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 that in other Southeast Asian countries, such as Singapore, Thailand, Indonesia, and several other countries [12,13]. However, the focus of carbon footprint research in the forestry, agriculture, municipal, transportation, and construction sectors is growing compared to that in 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 Senok desalination plant. The partnership between Tenaga Nasional Bhd.'s (TNB's) subsidiary Renewables Sdn. Bhd., the Energy Commission, and SEDA to adopt the Energy Tariff and Net metering system, is clearly an excellent solution if the results of this carbon footprint can be presented to the relevant decision makers.

Despite significant academic and local authorities' efforts towards the development of the latest technological desalination projects, the RO membrane performance has performed 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 maximize membrane performance, diameter operation, and water feed [14,15]. For example, a study by Shahzad et al. [16] proves that the roadmap of sustainable development in desalination plants can be achieved through the transition of several factors, including improving membrane performance, and innovative and high hybrid desalination technologies, such as thermally driven MED/MSF technology for high efficiency. The researchers suggest that a comprehensive review of the hybrid membranes, entropy concentration, and thermodynamic reduction has significant potential to improve energy saving and resource recovery, and additional studies are needed to control the effect of climate change. This study examined the potential contribution of the product, namely water, through carbon footprint measurement. Seawater was selected as the source for clean water transformation in Senok 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 study were to (1) review current flows of GHG emissions and carbon footprints in this SWRO system and (2) to evaluate the CF performance of the SWRO system, thus proposing long-term suggestions on the issue of carbon savings.

2. Materials and Methods

2.1. Initial Analysis

In order to obtain accurate data on the carbon footprint, inventory-based questionnaires were 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 Senok, Kelantan. Among the information that was deemed acceptable, only complete and analytical, numerical, and empirical data were available, including some validated and accepted laboratory test results. The LCA method, in accordance with ISO14040-43 guidelines [17,18], was simplified to, first, goal setting and scope. The working unit selected was 1 cubic meter of treated water produced from a salt water desalination source. The second step was the development of the content of the inventory data, in which the mining of material input data output was presented as an LCI chart. Third, life cycle impact assessment (LCIA) using Simapro 8.5 software was performed on a single inventory spreadsheet. The latter enabled 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 excluded carbon emissions from decorative materials because of data that are related to poor usability.

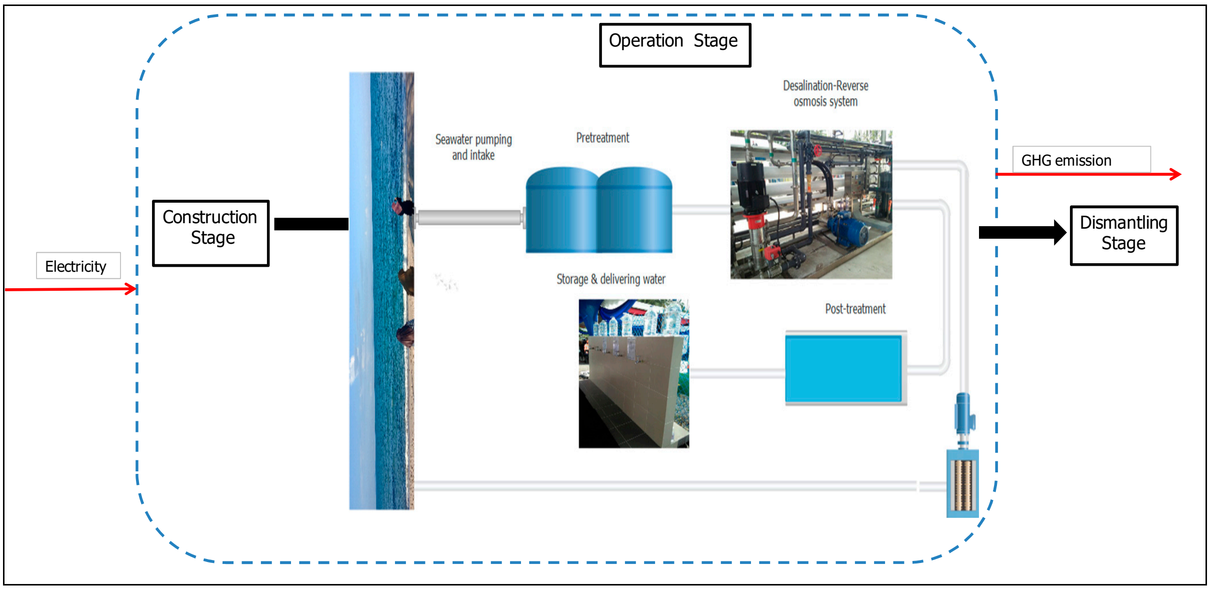

Figure 1. Conceptual images for seawater desalination system boundaries in Senok. The blue dotted point line indicates the boundary of the scope of the study.

2.2. Data Inventory

The inventory database for the construction and operation phases is arranged and presented in a spreadsheet in Table 1. 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 Senok desalination plant engineer and administrators of Bachok district, and the remaining data were obtained from Ecoinvent, Simapro [19].

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 2. The recycling of materials was not 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 shutdown 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 spreadsheet of inventory data of 1 m^3 of desalinated water production.

Inputs	Calculated Value	Unit	Source
Materials/fuels			
Reinforcing steel	3.96×10^{-4}	kg/m^3	Calculation
Polyethylene	1.75×10^{-4}	kg/m^3	Calculation
Chromium steel pipe	1.90×10^{-4}	kg/m^3	Calculation
Concrete, 30–32 MPa	2.79×10^{-5}	kg/m^3	Calculation
Steel	2.76×10^{-5}	kg/m^3	Calculation
Nylon	1.41×10^{-3}	kg/m^3	Calculation
Polypropylene resin	1.96×10^{-3}	kg/m^3	Calculation
Electricity			
Pumping seawater	3.00×10^{-1}	kWh/m^3	Calculation
Pre-treatment	1.50×10^{-1}	kWh/m^3	Calculation
Reverse Osmosis	2.40×10^{0}	kWh/m^3	Calculation
Wastewater	2.50×10^{-1}	kWh/m^3	Calculation
Post-treatment	1.70×10^{-1}	kWh/m^3	Calculation
Storing + distribution	1.00×10^{-1}	kWh/m^3	Calculation
Chemical products			
Polyaluminium chloride	2.70×10^{-3}	kg/m^3	Ecoinvent 3
Polyacrylamide	1.80×10^{-3}	kg/m^3	Ecoinvent 3
Soda ash	1.50×10^{-1}	kg/m^3	Ecoinvent 3
Hydrochloric acid	4.50×10^{-3}	kg/m^3	Ecoinvent 3
Sodium hydroxide	5.40×10^{-3}	kg/m^3	Ecoinvent 3
Chlorine	1.00×10^{-3}	kg/m^3	Ecoinvent 3
Sodium hydrogen sulphite	1.08×10^{-2}	kg/m^3	Ecoinvent 3
Sodium hypochlorite	5.40×10^{-3}	kg/m^3	Ecoinvent 3
Calcium carbonate	5.40×10^{-3}	kg/m^3	Ecoinvent 3

Table 2. The gross estimation of raw materials in the construction phase.

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 floors, steel frames, roofs, locks
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.

2.3. Calculation of GHG Emission

In the estimation of the potential GHG emissions, the IPCC 2013 approach was adopted, which is the global warming potential (GWP) for a period of 100 years [20]. Table 3 shows the sustainability composition values for a RO desalination plant with local electrical energy sources. The basic solution to calculate the CO_2 equivalent emission factor and carbon footprint used Equations (1) and (2), with the values of 1, 21, and 310 for GWP multipliers [21,22]. However, this study did not consider the embodied energy and embodied GHG emissions.

$$\text{Emission Factor (kg } CO_2 \text{ eq/kWh)} = 1 \times (\text{kg } CO_2/\text{kWh}) + 21 \times (\text{kg } CH_4/\text{kWh}) + 310 \times (\text{kg } NO_2/\text{kWh}) \quad (1)$$

$$\text{Carbon Footprint of Products (CFP) (kg } CO_2 \text{ eq/m}^3) = [CO_2 \text{ eq (kg/kWh)} \times \text{Electricity Utility of company (kWh/yr)}] \div \text{Water Produced (m}^3\text{/yr)} \quad (2)$$

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. CO_2-eq Emissions in the Construction Process

The Senok 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 during its early phases of construction due to reliability issues with the initial raw data, such as that relating to utilities, including electrical and water consumption and human resources, piling/ground work, land clearing, energy recovery devices, filters and membranes, and pumps. 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 CO_2-eq, followed by polyethylene and trucks at 3.51×10^{-5} and 6.19×10^{-6} kg CO_2-eq, respectively. The total GHG emission was 1.46×10^{-4} kg CO_2-eq, which accounted for 55% of this phase. Several important steps can be implemented in the future to reduce the GHG emission by requiring specific reporting, such as an environmental impact assessment (EIA). However, in this study, the EIA report was not necessary due to the small plant scale [23]. In terms of materials, the cost-saving factor in the procurement of certain raw materials can also reduce the carbon footprint [24,25]. Moreover, the introduction of an incentive policy of Renewable Energy Power Purchase Agreements, under the FiT: Feed-in-Tariff and "MyPower" mechanism by KeTTHA and TNB, for the SWRO Senok plant, should be reviewed in terms of feasibility.

3.2. CO_2-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 CO_2-eq/year, with the assumption that the contribution was not significant and considerably smaller when compared with some studies conducted in other countries, as shown in Table 4. The other contributing factors are plant capacity, adaptation of technology, fuel type, and the selection of the attribute calculation in scopes 1, 2, and 3. In this study, the three dominant phases contributing to carbon footprint were reverse osmosis operation, accounting for 75% (2.6×10^{-2} kg CO_2-eq per m^3), seawater intake at 12% (3.2×10^{-3} kg CO_2-eq per m^3), and post-treatment (2.5×10^{-3} kg CO_2-eq per m^3).

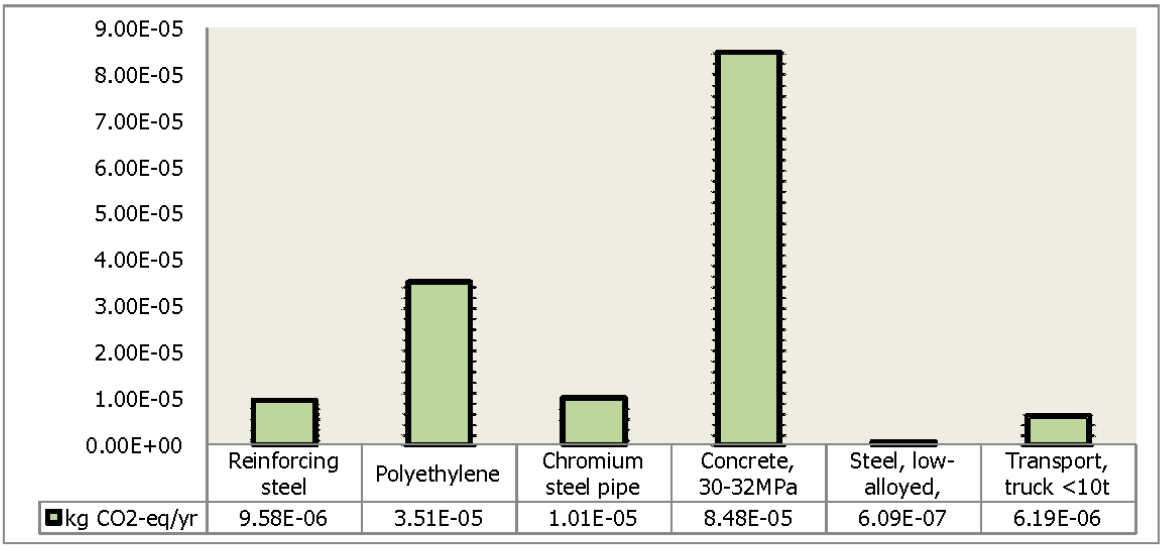

Figure 2. GHG emissions for the Senok SWRO desalination construction stage.

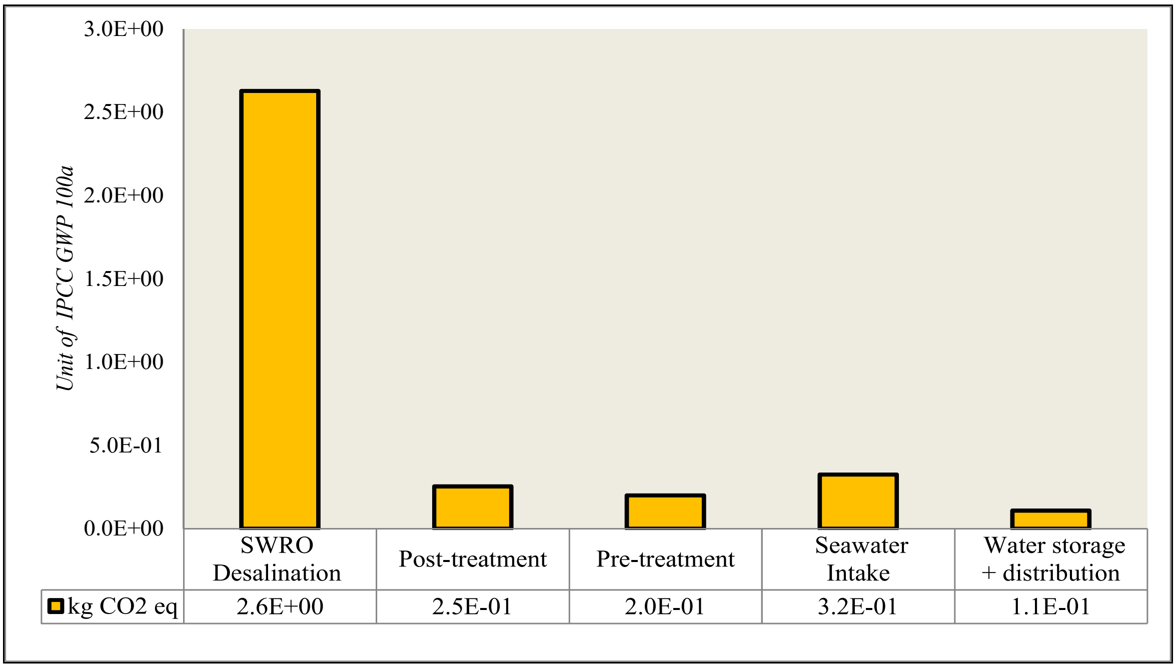

Figure 3. Contribution of relative carbon footprint, according to phase of process, by SWRO in the operation stage.

Table 4. Comparison of carbon footprint emissions from Malaysia and other countries.

Countries	Total Carbon Footprint (kg CO_2)	Study
Spain	1.59–5.63 kg	Liu et al. [21]
Israel	2.21–7.46	Pablo et al. [26]
United Arab Emirates (UAE)	2.56	Biswas and Yek [27]
China	2.10–3.60	Xuexiu et al. [25]
Malaysia	0.035	Present study

The intensive application of 100% fossil fuel to generate electricity for the SWRO plant was identified as the major factor in the increase of carbon and GHG emissions, 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 emissions based on the evaluated process phase. Notably, a further study is needed for the phases of manufacturing, transportation, and membrane because the GHG emissions from these phases complement the results of the carbon footprint for the SWRO system. The current research suggests the new capacity of the SWRO operation, which is not yet fully functional and has been in operation for less than one year, could be a contributing factor to the low relative carbon footprint.

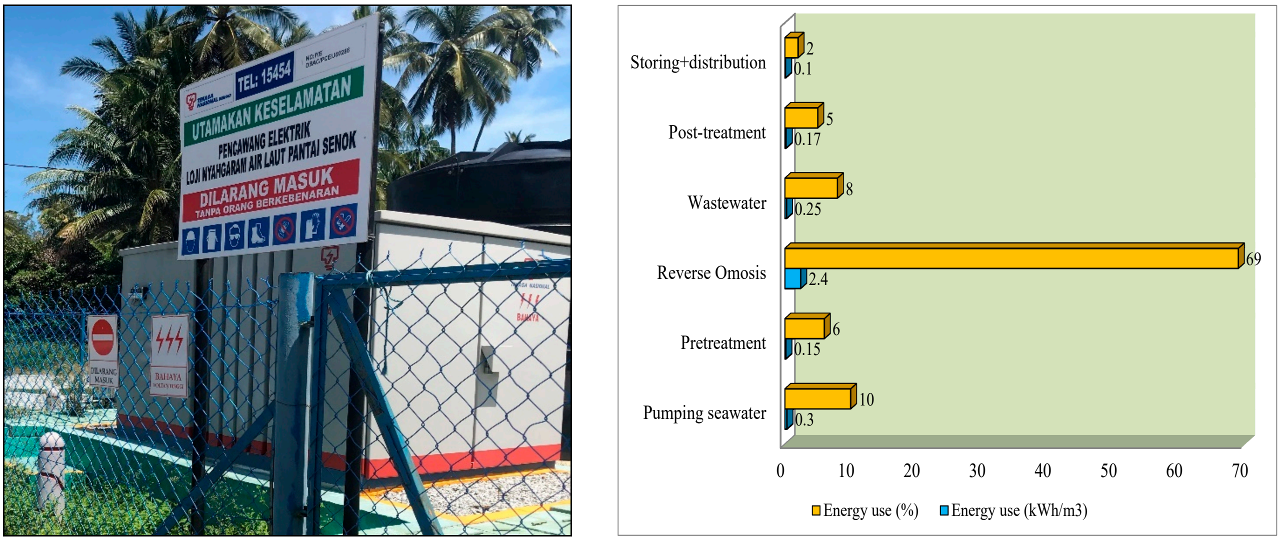

Figure 4. TNB's electric power generating system covers the transmission and distribution of electricity, according to the SWRO process stage in Senok, Kelantan.

Figure 5 depicts the intensity of quantitative uncertainty for the operation stage, with mean, median, and standard deviation values of 3.71, 3.70, and 0.01 kg CO_2 eq, respectively. Based on this, it is concluded that the standard deviation is within a reasonable range with a 95% confidence interval. This outcome was predicted because several factors contributed to the dominant effect on value, including information uncertainty, a lack of valid and stochastic values in the inventory base, limitations of model selection aspects, valuation methods, the allocation, and variability of background data for operating systems. Uncertainty variables are related to data reliability, completeness, geographical correlation, temporal correlation, technical correlation, and sample size difficulties, according to the report of Baek et al. [24]. Furthermore, the increase in uncertainty scores shown in the figure below is due to the characterization analysis of emission variables (types of effect categories: carcinogen, organic respiration, inorganic respiration, climate change, ozone layer, ecotoxicity, acidification), soil use, and resource depletion. As a result, the evidence supporting this hypothesis suggests that using proper models and approaches, in addition to actual data, can more sustainably improve the performance of the carbon footprint assessment at this stage. Finally, there is a potential for enhancing the long-term viability of the desalination system.

Based on the percentage contribution between chemicals and electricity shown in Figure 6, the results are in agreement with those that were reported in Biswas [28], Sydney water, Cooley and Heberger, and Shahabi et al. [29–31]. The utility of electricity consumption was 3.613 kg CO_2-eq, which was determined using the IPCC GWP 100 analysis, as shown in Figure 3. In addition, 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 CO_2-eq (4%). According to Gobin et al. [32], 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. Furthermore, the potential of the 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 6, the change in electrical utility is significant at 96%, which is equivalent to 2.8 kWh/m^3 for water pumping, membrane operation, and water distribution to the main pipes. Based on the work by Raluy et al., Stokes and Orvath, and Elimelech and Philip [33–35], several best recovery steps for electricity include installing an energy recovery device, and optimizing the pump use and membrane permeability. Fahad et al. [22] proved that the use and increase in the diameter of a membrane can also reduce the carbon footprint due to the high rejection of boron, bromide, and other relevant materials. Moreover, the details of research by Abdul Ghani et al. [36], which undertook a more in-depth examination related to the membrane potential than in the case of Senok study, is more relevant for further study in the future.

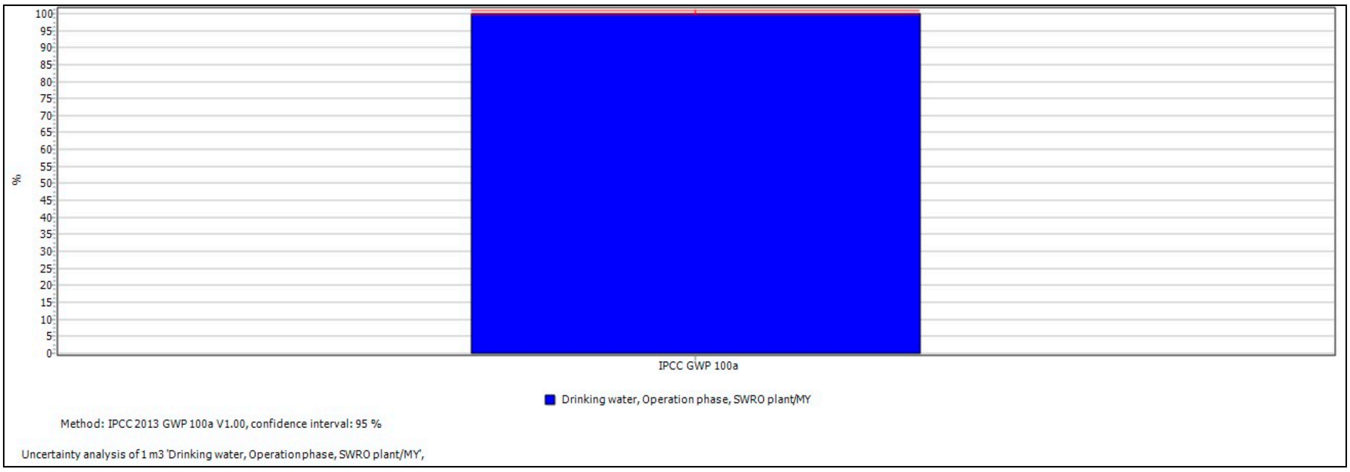

Figure 5. The results of the uncertainty analysis of this research.

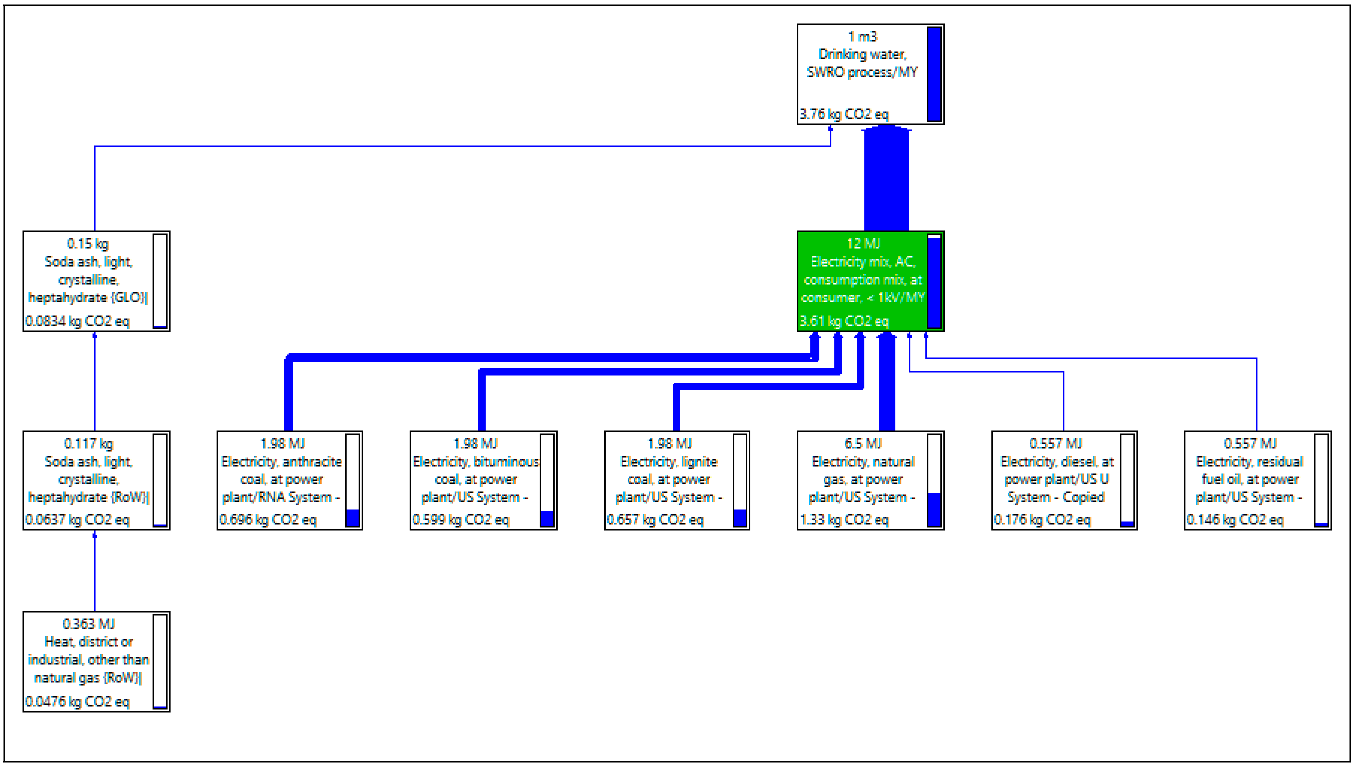

Figure 6. Dendrogram of the main contributions to GHG emissions per cubic meter of SWRO from chemicals (4%) and electricity (96%) factors.

As mentioned previously, this SWRO Senok pilot plant project was developed on a small scale with a capacity of 500 m^3 per day to cover a 3000 household population. The overall carbon emissions from the plant were small and resulted in an insignificant impact on the environment, as shown in Figure 7. The CO_2 emissions were the highest contributor, at 3.48×10^{-3} kg CO_2-eq, followed by methane at 2.70×10^{-4} kg CO_2-eq. The other pollutants included the emissions of NO_x and So_x, which were considered to be insignificant. These results are also consistent with the results of the Biswas and Yek study [27], which confirmed that the three major types of greenhouse gas emissions from decontamination operating plants are due to carbon dioxide, methane, and nitrogen dioxide gases. However, if the plant continues to operate completely on fossil fuel for the next 25 years, the emissions are expected to affect the health of the community. Fahad et al. [22] reported a similar pattern in their study, which found comparative results for CO_2 emissions for their RO plants in the construction and operation stages, respectively, of 3.0 kg CO_2 and 2.3 kg CO_2. These emissions contributed to increased variances for numerous reasons. For example, if immediate controls are not implemented in each operational desalination plant, factors such as heat emission, energy consumption, and fuel transportation based on the capacity of different RO plant sizes can have an impact on the environment. Thus, the greater the greenhouse gas emissions, the greater the carbon footprint produced by a factory or plant. In conclusion, the control of GHG emissions can meet the agenda of the Kyoto Protocol for local climate change mitigation.

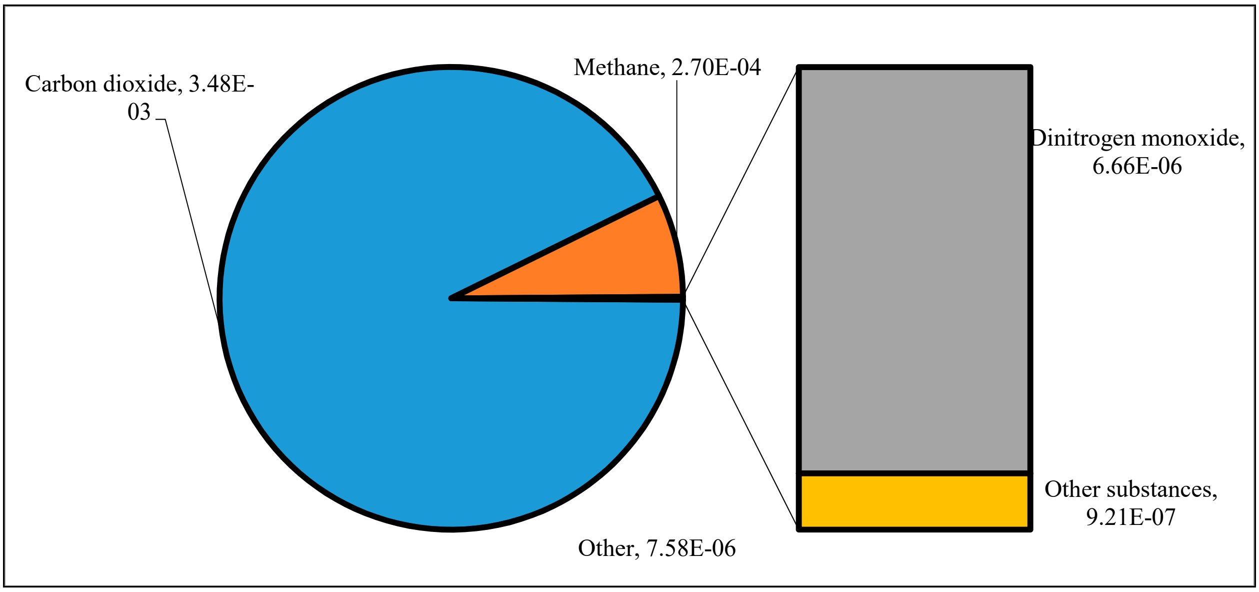

Figure 7. The relevant airborne (substance) emissions produced in kg CO_2 eq per 100 year period for the whole process of the SWRO system.

3.3. Relationship between Limitations, Strategies and Adaption

In the context of desalination research in Malaysia, carbon footprint indicators still require various innovations, especially in the preparation of 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 of energy emissions in Malaysia affects the reporting of the carbon footprint and delays the process of transition to the use of renewable energy. The study of the scope of the carbon footprint also requires a comparison between the sources of groundwater, brackish water, wastewater, and treated water because the community around Senok highly depends on the feed water sources. The largest issue relates to data loss and lack of information regarding material disposal, construction of plant infrastructure, tanks, and transportation services, which are needed to model the indirect carbon footprint emission. According to Gobin et al. [32], limited accessibility of data, such as chemicals and energy data via extraction using different models such as GaBi and West, is a major limitation in the research of carbon footprint desalination in Cape Town, Africa. Therefore, further research needs to be undertaken with the involvement of sensitivity analysis of 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 [37]. In addition, 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 the clean water credit issue.

Because the CF system boundary evaluated in this study was small, the carbon footprint calculation was focused on the direct estimation, rather than the indirect estimation, such as in the analysis 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. Moreover, several carbon footprint evaluation instruments, such as the WESTWeb model, CHEApet, Simulation Platform No.2 (BSM2G), Johnston tools, LCA hybrid tools, and other equipment can be used for more accurate estimates [38]. As mentioned previously, SWRO sustainability is related to an alternative selection to minimize environmental impact, and the integration between the different sources of energy with renewable energy was fundamentally selected to meet the objective. Other literature reviews have noted that the energy reduction via membrane technology increases up to 38% with the integration of the hybridized SWRO and other renewable energies [28]. The replacement of fossil fuel in the current desalination process is also expected to reduce the cost of clean water production in Senok.

Previous studies have reported a similar finding in terms of CF impact, showing an inverse correlation between the conventional desalination system versus desalination and carbon emissions [39,40]. Studies have also reported that the introduction of a dummy process via integration of Conventional Electrodialysis (ED) or Bipolar Membrane Electrodialysis (EDBM) has successfully reduced the GHG emissions to zero [41–43]. Therefore, the trend changes in the carbon footprint profile and the environmental load recovery performance are expected to occur frequently because carbon emissions from the desalination sector affects global climate change. Based on this study, a further study is proposed to detail the low carbon development policy by compiling novel process outcomes, an inventory, and the LCA effect category. This future study will provide a better understanding for policymakers at the national and local levels.

4. Conclusions

The sources and impacts of significant and non-significant producers of GHG and CO_2 emissions on the performance of a small-scale SWRO in Senok were investigated in the carbon footprint mode. Several conclusions can be drawn from this study:

- The total dependency of the electrical source for the SWRO process of fossil fuel was the most critical factor in the carbon footprint issue in this study. However, the GHG emissions from the SWRO plant (3.5×10^{-2} kg CO_2-eq/yr) represented a 30- and 39-fold deficit compared to desalination treatment plants in Carnoneras, Spain, and Australia, respectively [28]. This value was affected by minimum chemicals, the performance of new membrane technology, the small plant capacity, land area, water feed, and intermittent operating duration.
- The option of renewable energy and an integrated desalination system (state-of-the-art desalination technologies) could reduce the GHG emission to 90% (based on the findings of Shahabi et al. [31,44], which is equivalent to 1.09×10^{-1} kg CO_2-eq/year for this SWRO plant.
- These findings can be used to develop a carbon footprint model that can commercialize carbon tax, carbon economy capital, energy security assurance, and standard carbon regulation and legislation in the context of local desalination projects. How-

ever, a further study on the financial investment factor related to new desalination technology adaptation is critical.

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