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A forecast for the environmental effect of pressure-retarded osmosis on CO_2 emissions from seawater reverse osmosis in Korea: a scenario-based study

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ABSTRACT

Seawater reverse osmosis (SWRO) has played a key role in alleviating water stress worldwide. However, its intensive energy consumption, which is highly dependent on fossil fuels, needs to be reduced to mitigate the CO_2 emissions resulting from SWRO. Many technologies, including pressure-retarded osmosis (PRO), have been applied in an attempt to reduce the energy consumption of SWRO. In this study, potential trends in CO_2 emissions from SWRO processes in Korea are considered based on SWRO operational data collected from a range of sources and relating to societal scenarios of the future. These societal scenarios are based on current population trends in Korea and the proportion of renewable energy currently utilized in Korea. Next, using a dimensionless performance index for the SWRO-PRO hybrid process, the study presents the potential efficacy of PRO in reducing the magnitude of CO_2 emissions from SWRO processes in Korea. The analysis shows that CO_2 may be reduced by 10%–40%. The results of the study suggest a promising role for PRO as a suppressor of CO_2 emissions. It is anticipated that the study will facilitate further in-depth studies into the use of PRO.

Keywords: Reverse osmosis; Pressure-retarded osmosis; Modeling; Global warming; Carbon dioxide emissions

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1. Introduction

Global warming is one of the most controversial issues of the 21st century. Around the world, countries are attempting to find the best solution for mitigating global warming. Recognizing the need for international cooperation if this goal is to be achieved, the Paris Agreement, the largest global climate change agreement in history, was ratified in 2015. According to this agreement, Korea must reduce its own greenhouse gas emissions by 37% relative to its current levels by 2030 [1,2].

In many countries, seawater reverse osmosis (SWRO) has played a significant role in relieving the water stress resulting from climate change [3]. Despite considerable technological advances in SWRO in recent decades, this process is still considered energy-intensive [4–7]. Thus, SWRO may have severe negative impacts on global warming because fossil fuels currently generate most of the electricity needed to operate the process. To resolve this paradox, a strategy employing pressure-retarded osmosis (PRO) in conjunction with SWRO is considered an effective approach to reducing the energy consumption of SWRO while maintaining the same water productivity [8–11]. However, the effects of the hybrid SWRO-PRO process on climate change have been little researched to date. Even those studies that have investigated the carbon footprint of desalination processes have not provided any clarity on this topic [12,13]. Therefore, the effects of the SWRO process on

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climate change and the extent to which CO_2 emissions can be reduced through PRO warrant further investigation.

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2. Materials and methods

2.1. Conversion of SWRO energy consumption into CO_2 emissions

In this study, the reports, including the datasets, provided by three institutions are considered with a view to securing operational data for SWRO processes in Korea (Table 1).

By utilizing the datasets given in Table 1, the collected data was processed to identify the overall effects of SWRO processes on CO_2 emissions. After the initial processing, the CO_2 emission magnitude was broken down into three variables, as follows, to conduct the analysis.

$$\mathrm{MEM}_{\mathrm{CO_2}}\left[\frac{\mathrm{kgCO_2}}{\mathrm{d}}\right]=\mathrm{CAP}\left[\frac{\mathrm{m}^3}{\mathrm{d}}\right]\times\mathrm{SEC}\left[\frac{\mathrm{kWh}}{\mathrm{m}^3}\right]\times\mathrm{Eff}\left[\frac{\mathrm{kgCO_2}}{\mathrm{kWh}}\right] \tag{1}$$

where $\mathrm{MEM}_{\mathrm{CO_2}}$ stands for the total emission magnitude of CO_2 resulting from SWRO processes; CAP stands for the capacity of the SWRO processes; SEC stands for the specific energy consumption of the particular process; and Eff is the magnitude of CO_2 emissions relative to the unit energy consumption. To assess how much PRO can reduce the energy consumption of SWRO, the current study utilizes a dimensionless index developed for PRO-hybridized processes [14] (Variable 2 in Fig. 1). In this study, the recent CAP and SEC data were taken from the datasets referenced in Table 1. The CAP data for SWRO processes in Korea were separately extracted from Dataset 3, and it is assumed that the SWRO energy consumption in Korea follows the global SEC data trend. Using the recent data, future trends in CAP and SEC are extrapolated. In contrast to CAP and SEC, Eff is not the conventional data for membrane-based desalting processes since it is dependent on local energy generation facilities, which will differ according to the policies and technological advances of each country. Therefore, unlike CAP and SEC, it may not be said that a single Eff value can represent the environmental soundness of the membrane-based desalting

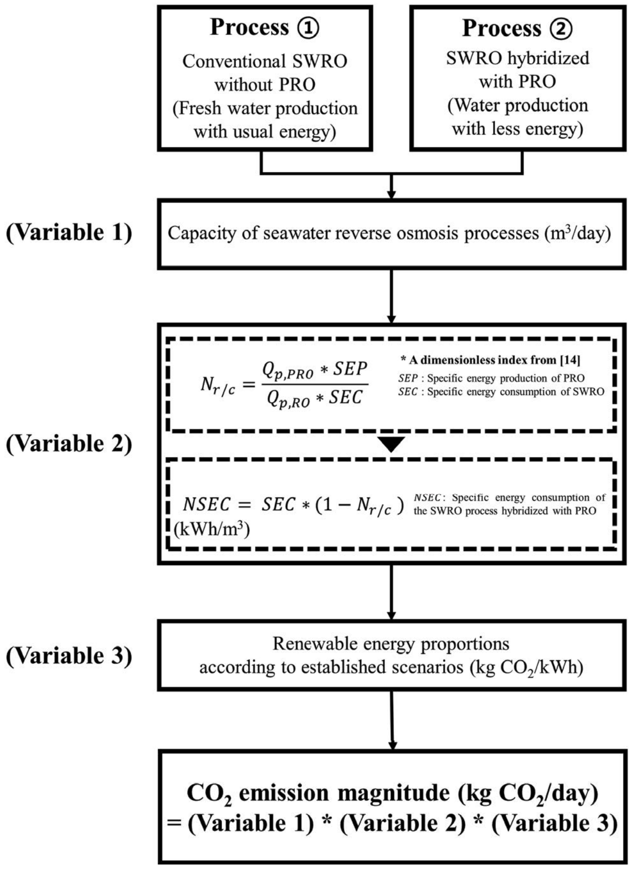

Fig. 1. Flowchart representing a method for estimating the magnitude of CO_2 emissions from SWRO processes in Korea and for calculating the effects of a PRO process in reducing the magnitude of the CO_2 emissions.

Table 1
References used to analyze the magnitude of CO_2 emission from SWRO

Index	Title	Institution	Year	Reference
Dataset 1	Potential impacts of desalination development on energy consumption	European Energy Commission	2008	[15]
Dataset 2	Key issues for seawater desalination in California: energy and greenhouse gas emissions	Pacific Institute	2013	[16]
Dataset 3	Desalination and water reuse	Global Water Intelligence (GWI)	2017	[17]

processes. In this context, all the data referenced for the current study had designated Eff values that were different. Likewise, the values for Eff in the current study should be determined individually. The determination of Eff for the current study is addressed in a subsequent section. Once each variable is established for a future scenario, the CO_2 emission magnitude of SWRO processes in Korea can be estimated (Fig. 1).

2.2. Future scenarios for SWRO capacity in Korea

According to Dataset 3 in Table 1, the total operating capacity of the SWRO process in Korea has continuously increased (Table 2). That is, demands for SWRO processes are gradually increasing in Korea. Furthermore, the total operating capacity is predicted to increase still further in the foreseeable future.

However, it cannot be assumed that the total operating capacity of SWRO processes in Korea is going to increase indefinitely into the future since the current population expansion in Korea will only be sustained until 2030 [18]. After 2030, unless the current birth rate in Korea changes, it is predicted that the total population will decrease dramatically. Therefore, future demands for SWRO processes should be viewed according to anticipated changes in the Korean population. Due to the uncertainties regarding the future, three different scenarios for future demands for SWRO processes are established, as presented in Table 3. Scenario 1 (A1) in Table 3 assumes that the total operating capacity of domestic SWRO processes will continue to increase at the same rate as during the period 2013 to 2022. Scenario 2 (A2) assumes that the capacity of the processes will increase until 2030, together with the anticipated increase in the Korean population, and will then maintain a constant level. Lastly, Scenario 3 (A3) assumes that the capacity of the SWRO processes will follow the trends in the rise and subsequent fall in population numbers. In this study, the future demands for SWRO processes will be viewed differently on the basis of these three scenarios.

Table 2
Total operating capacity of SWRO processes in Korea from 2001 to 2017, showing annual increase and projected future capacity [17]

Year	Total operating capacity (m^3/d)
2001	66,900.1
2002	67,308.1
2003	67,308.1
2004	67,308.1
2005	67,308.1
2006	67,308.1
2007	67,308.1
2008	69,858.1
2009	70,495.6
2010	73,725.6
2011	73,725.6
2012	73,725.6
2013	158,062.6
2014	183,668.9
2015	183,668.9
2016	181,059.7
2017	182,299.1
2018	187,803.2
2019	193,402.4
2020	201,205.1
2021	211,708.0
2022	224,592.4

2.3. Future scenarios for the proportion of renewable energy vs. fossil fuel

Future scenarios for the renewable energy proportion of electricity generation in Korea can also be established. According to the forecast data from the Korean Federation for Environmental Movement [19], two different scenarios can be assumed for the proportion of renewable energy in the future (Table 4). The first scenario is called 'high fossil fuel reduction' (B1), and this states that the proportion of fossil fuel used for generating electricity in Korea will be reduced by more than 40% by 2050. The second scenario is called 'low fossil fuel reduction' (B2), and this scenario assumes that by 2050, the proportion of fossil fuels will be reduced by 20% to 30% as compared to the current status. In both scenarios, it is assumed that fossil fuels must ultimately be completely replaced by renewable energy sources (i.e., no other energy generation methods, such as biomass, are considered). Furthermore, it is assumed that the amount of CO_2 emitted by renewable energy sources is negligible. Therefore, the remaining proportions of fossil fuels (i.e., {100–renewable energy proportions given in Table 4} %) are considered the factors incurring the CO_2 emissions.

As described above, the values of Eff are utilized in a particular way. The first step in estimating future Eff ($\text{Eff}_{\text{future}}$) for the current study is to fix the reference value of Eff (Eff_{ref}). After fixing the reference value, $\text{Eff}_{\text{future}}$ is estimated by multiplying Eff_{ref} by a ratio of the fossil fuel proportion formed by the target year and the current year. That is, $\text{Eff}_{\text{future}}$ can be calculated as:

$$\text{Eff}_{\text{future}} = \text{Eff}_{\text{ref}} \times \frac{\left(\text{fossil fuels proportion of target year}\right)}{\left(\text{fossil fuels proportion of 2020}\right)} \tag{2}$$

Thus, Eff in (Eq. (1)) is replaced by $\text{Eff}_{\text{future}}$ in (Eq. (2)) in order to forecast CO_2 emission magnitude. Since the fossil fuel proportion scenarios are already established, finding the most suitable Eff_{ref} is the last thing needed to estimate $\text{Eff}_{\text{future}}$. As shown in Table 5, the three references used in the current study estimated Eff_{ref} differently. Such different estimations of Eff_{ref} are attributed to the varying policies in each country and technological discrepancies in relation to fossil fuels. Incorporating all those values into the prior scenarios may undermine the reliability of the current study results since the total number of scenarios used for forecasts then becomes eighteen. Therefore, only the value for Eff_{ref} drawn from Dataset 3 is utilized

Table 3
Future scenarios for demand for SWRO processes according to population trends in Korea

Scenario 1 (A1)	Scenario 2 (A2)	Scenario 3 (A3)
Total operating capacity of domestic SWRO processes will increase continuously at the same rate at which it increased during the period 2013 to 2022	Total operating capacity of SWRO processes will increase until 2030, together with the increasing trend of the domestic population, and will thereafter keep constant	Total operating capacity of the SWRO processes will follow trends in the size of the domestic population

Table 4
Future scenarios for the proportion of fossil fuels used in Korea

	2020	2025	2030	2035	2040	2045	2050
Scenario 1 (%) (High fossil fuel reduction, B1)	57.15	46.36	37.61	30.51	24.75	20.08	16.29
Scenario 2 (%) (Small fossil fuel reduction, B2)	55.67	50.21	45.29	40.85	36.85	33.24	29.98

Table 5
CO_2 emissions relative to unit energy consumption as drawn from various source documents

Sources	Eff (kg CO_2/kWh)
Dataset 1	0.408
Dataset 2	0.323
Dataset 3	0.500

in the current study. There are two other reasons for this choice: First, Dataset 3 is the most recent reference that the current study is utilizing. Thus, it could be assumed that Dataset 3 is more trustworthy than others. Second, Dataset 3 shows the worst scenario in terms of CO_2 emissions from fossil fuels. Considering that the objective of the current study is to speculate on the future environmental soundness of SWRO processes, it is preferable to conduct the study using the worst-case scenario rather than optimistic scenarios. Thus, the value of Eff_{ref} for the current study is the one drawn from Dataset 3.

3. Results and discussion

3.1. Relationship between SWRO energy consumption and CO_2 emissions

Fig. 2 represents the global distribution of SEC, using data extracted from Dataset 3, together with CAP. Since the magnitude of the SWRO capacity varies greatly according to the purpose and location of each process, logarithms are taken for the values of CAP to show clearly the whole distribution of SEC. As shown in Fig. 2, the variables CAP and SEC do not have a clear relationship.

However, as shown in Fig. 3, the total energy consumption per day of SWRO processes and their capacity show

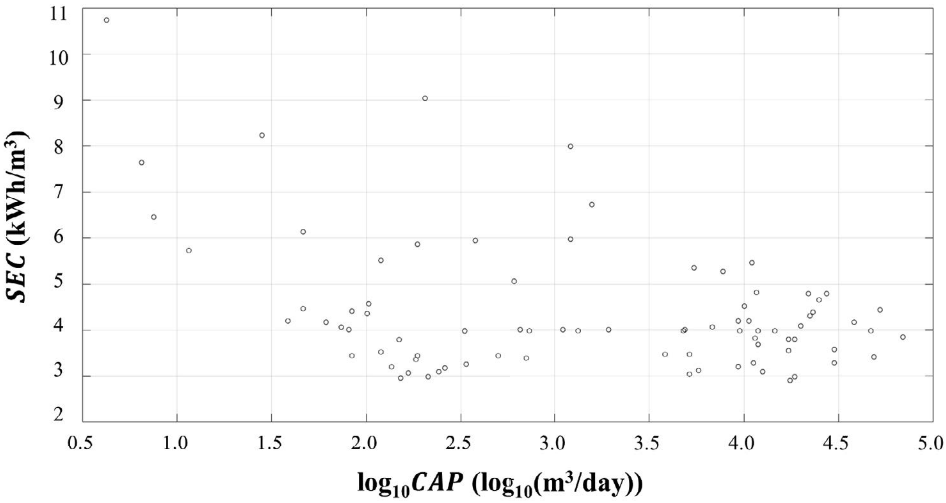

Fig. 2. The figure represents the specific energy consumption (SEC) data for SWRO processes around the world according to their capacity (CAP) [17].

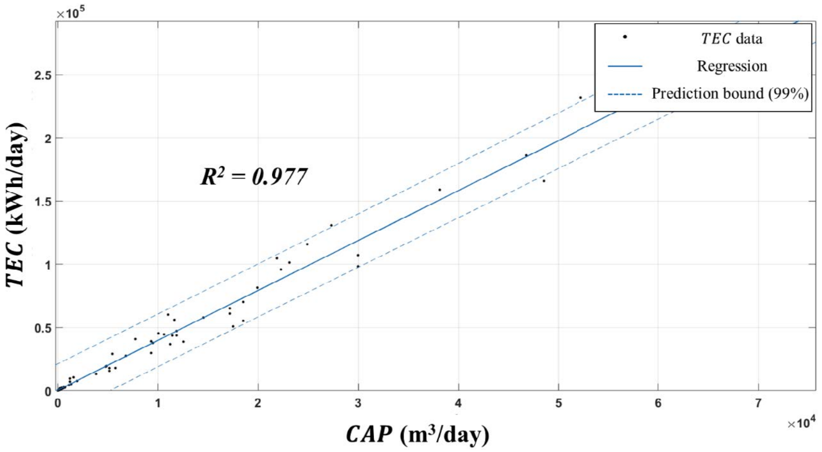

Fig. 3. A plot diagram showing a linear relationship between the total energy consumption per day (TEC) and the capacity (CAP) of SWRO processes [17].

a clear linear relationship. (Hereinafter, the total energy consumption per day of SWRO is denoted as TEC, and is defined as the product of CAP and SEC). The relationship demonstrated in Fig. 3 is a significant result because the capacity of the SWRO process can be related to the magnitude of CO_2 emission by using this relationship. That is, the CO_2 emission magnitude can be forecast according to the capacity of SWRO processes provided the fossil fuel scenarios are taken into consideration.

3.2. Forecast of CO_2 emissions from SWRO processes according to the scenarios established

This subsection reveals the forecasted results for CO_2 emissions as based on the scenarios introduced in the materials and methods section. Six additional combination scenarios are forecast based on combinations of the total population scenarios (Table 3) and the fossil fuel scenarios (Table 4), and the magnitude of CO_2 emissions from SWRO processes in Korea.

Table 6 represents the combination scenarios used for the prediction tasks of the current study. A new term, combination scenario, is abbreviated as combination scenario (CS) hereinafter for convenience.

As shown in Fig. 4, it was found that two types of CO_2 emission magnitude prediction can be made in relation to domestic SWRO processes. The predictions made for CS2, CS3, CS5, and CS6 clearly show a decreasing tendency in the CO_2 emission magnitude. However, predictions made in relation to CS1 and CS4 display an increase in CO_2 emissions from domestic SWRO processes. Given that CS1 and CS4 are scenarios based on the assumption that the demand for SWRO processes is going to continuously increase, it could be concluded that the proposed reduction in the proportion of fossil fuels cannot cope effectively with the increased CO_2 emissions from the SWRO processes. Hence, the need for additional renewable energy sources that can replace the SWRO process with its CO_2 emissions. That means that more efficient renewable energy facilities and relevant infrastructures are desperately needed to mitigate the magnitude of CO_2 emissions regardless of SWRO capacity scenarios.

Furthermore, despite very different total population scenarios, it is evident that the capacity scenarios A2 and A3 show almost equivalent forecast results in Fig. 4.

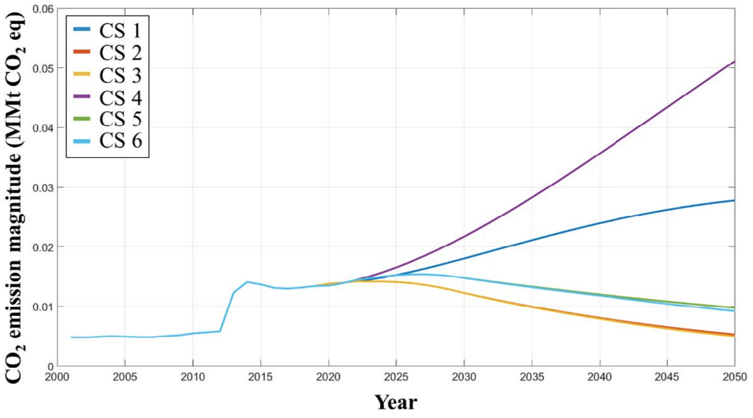

Fig. 4. A figure displaying the simulated results of CO_2 emission magnitude from Korean SWRO processes, as predicted by the scenarios established in the materials and methods section.

Table 6
Final scenarios used to forecast CO_2 emissions from SWRO processes

Scenario types	A1	A2	A3
B1	Combination scenario 1 (CS1)	Combination scenario 2 (CS2)	Combination scenario 3 (CS3)
B2	Combination scenario 4 (CS4)	Combination scenario 5 (CS5)	Combination scenario 6 (CS6)

(CS2–CS3 and CS5–CS6) Such similarities in the forecast results are somewhat surprising since the gap between CS1 and CS4 is far greater than those between CS2–CS3 and CS5–CS6. From these forecast results, two other conclusions can be drawn. First, there is a specific point where the dominant scenario of the overall forecast results is changed. In other words, the declining trend in fossil fuel proportion contributes to mitigating the magnitude of the CO_2 emissions up to a certain point, but shortly after that point, the increased demands for capacity take precedence in determining the magnitude of the CO_2 emissions. Tracking this conversion point may be a meaningful project for the future. Second, the demands for SWRO capacity may not be such a crucial factor as expected unless it continues to increase unceasingly. As shown in Fig. 4, every scenario except for CS1 and CS4, which include the A1 scenario, results in a decline in CO_2 emission magnitude. In other words, the demands for SWRO processes become a significant factor in determining the CO_2 emission magnitude only when they increase unceasingly.

In short, the magnitude of CO_2 emission from SWRO processes in the future is determined by a subtle balance between future demands for SWRO in relation to population growth and renewable energy utilization.

3.3. Evaluation of PRO efficacy for mitigating SWRO CO_2 emissions

Thus far, a series of predictions have been made for the future magnitude of CO_2 emissions from SWRO processes in Korea. Fortunately, four out of the six scenarios show that future CO_2 emission magnitude may decrease without particular measures. However, two of the scenarios provide a warning that the magnitude of CO_2 emission could

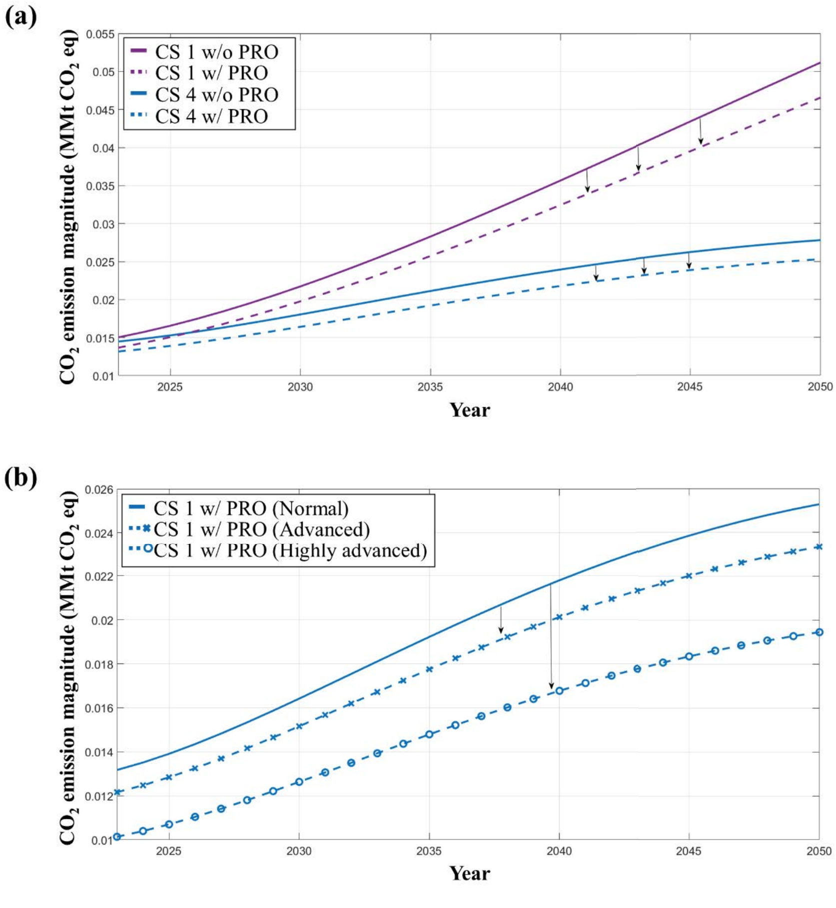

Fig. 5. These figures display the extent to which CO_2 emissions can be reduced by employing PRO in the SWRO processes in Korea. (a) The comparison between conventional SWRO processes and SWRO-PRO processes for CS1 (violet) and CS4 (blue). (b) The potential efficacy of future PRO processes on the reduction of CO_2 emissions from SWRO processes as the technology advances.

be greater than it is now. Thus, proper strategies for SWRO processes should be designed to prepare for this contingency.

As mentioned above, PRO is an appropriate technology for mitigating the magnitude of CO_2 emissions from SWRO processes. The PRO process generates freely-usable energy by directly utilizing the brine discharged from the SWRO processes. Since the energy source of PRO is theoretically carbon-free, SWRO processes that employ PRO technology can significantly reduce the magnitude of their CO_2 emissions in the long term. Figs. 5a and b illustrate how much CO_2 emission magnitude can be alleviated when PRO processes are paired with SWRO processes in Korea. The reduction in CO_2 emission magnitude is estimated by a performance index taken from a previous study (Fig. 1). As clearly shown in Figs. 5a and b, the PRO process can decrease the CO_2 emission magnitude of SWRO processes by between 10% (normal PRO) and 40% (highly advanced PRO). Here, 'normal PRO' stands for a PRO process in which performance is moderate. The performance of normal PRO is comparable with a state-of-the-art PRO process at present. The 'highly advanced PRO' is the best version of a PRO process hopefully, to be achieved in the future.

Figs. 5a and b indicate the promising role of PRO as a CO_2 suppressor. Although the current PRO can mitigate the CO_2 emission of the SWRO process to a certain extent, the effect of PRO on SWRO can vary considerably depending on future technological advances. Hence, in-depth studies concerning PRO should be conducted to maximize CO_2 mitigation efficacy.

4. Conclusions

For a long time, an important mission of researchers has been to mitigate global warming by alleviating the harmful impacts of greenhouse gases, including CO_2. Desalination technologies take credit for relieving water stress worldwide, but their energy consumption needs to be reduced. The intensive energy consumption of SWRO, the most popular desalination process, requires high operational costs and results in massive CO_2 emissions. Therefore, the energy consumption of SWRO processes needs to be controlled. In this context, this study forecasts the extent to which CO_2 emissions could be mitigated by combining PRO with SWRO processes in Korea. PRO is one of the most promising renewable energy technologies in that this process generates eco-friendly energy by utilizing seawater and freshwater. Since the energy generated by PRO can be used to operate the SWRO, the overall CO_2 emission magnitude can be significantly reduced.

With this in mind, the study aimed to investigate the extent to which PRO can mitigate CO_2 emissions from SWRO. To do this, the current study first established six combination scenarios (CSs) to forecast the extent of future CO_2 emissions from SWRO processes. CSs are comprised of 'total population scenarios' (Table 3) and 'renewable energy proportion scenarios' (Table 4). According to the forecast results, two CSs of the six show that future CO_2 emissions from SWRO processes in Korea may be greater than now due to increased demand. It can be concluded that in these situations it may be necessary to apply PRO to the SWRO processes to adequately suppress the magnitude of CO_2 emissions. In order to investigate the efficacy of the PRO process on SWRO processes in greater detail, the current study makes predictions for the potential reduction in CO_2 emissions in relation to future technological advances in the PRO process. The results suggest that CO_2 emissions from SWRO processes can be reduced by between 10% (with current PRO) and 40% (with highly advanced PRO) in the future. In light of these results, it is anticipated that the current study will serve to facilitate research into the use of improved PRO for alleviating the magnitude of CO_2 emissions from desalination processes.

Acknowledgments

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