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The mitigation of CO2 Emission in the Sea Water Desalination Plant with Reverse Electrodialysis Power Generation

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ABSTRACT

Climate change is a major issue that is very interesting to discuss. Climate change is believed to be caused by the greenhouse gas effect. CO_2 is one of the gases that causes the greenhouse gas effect. Therefore, to avoid the dangers of climate change, reducing CO_2 emissions is the main topic in various articles. In this article, CO_2 emission mitigation is analyzed in the sea water desalination plant using reverse electrodialysis power generation. Reverse electrodialysis is a power plant that does not produce CO_2 emissions which converts energy from the difference in salinity of two solutions into electrical energy through selective ion membrane technology. There are 8 sea water desalination (SWD) unit which produces 242 tons/h of clean water for industrial activity and blowdown water of 3,161 tons/h, the blowdown water is wastewater. The SWD unit requires 3.043 tons/h of seawater as feed water, 0.164 MW of electricity and 86 tons/h of steam worth 64.1 MW as an energy. The energy are met from the combined heat and power operation. Combined heat and power require of fuel oil and fuel gas which produce CO_2 emissions of 1,352,445,626 $kgCO_2/y$. From the analysis on the SWD plant, the CO_2 emission is 148,411,874 $kgCO_2/y$. By implementing reverse electrodialysis power generation, blowdown water at the SWD plant which has a salinity concentration of 680 mol/m^3 can produce electricity of 0.414 MW (3,636 MWh/y). If the electricity generated is used to substitute the electricity needs at the refinery plant, the CO_2 emissions that can be mitigated is 2,955,915 $kgCO_2/y$.

Keywords : CO_2 emission, sea water desalination, reverse electrodialysis

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1. Introduction

Climate change occupies the highest position as a cause of global disasters such as natural disasters, extreme weather, food and clean water crises, loss of biodiversity, and collapse of ecosystems. [1]. The biggest cause of climate change is an increase in the earth's surface temperature (global warming) which occurs due to increased concentrations of greenhouse gases (GHG) [2]. The source of global GHG emissions based on the type of GHG gas, the largest order comes from CO_2 emissions (76%), then followed by CH_4 (16%) and N_2O (6%) [3]. Meanwhile, by economic sector (including land use change), the largest contributors to GHG emissions are electricity and heat production (25%), agriculture and other land use (24%), industry (21%), transportation (14%), other energy (10%) and buildings (6%) [3]. In fact, the technological advances that we enjoy today are built on the use of fossil fuels such as electricity and transportation which produce a lot of GHG emissions, especially CO_2. Therefore, an increase in the effect of greenhouse gases cannot be avoided and disasters due to climate change are starting to arrive. To avoid the dangers caused by climate change is to reduce the production of CO_2 emissions by diverting the use of fossil energy with renewable energy.

Reverse electrodialysis (RED) is a form of renewable energy source that is environmentally friendly because it does not produce CO_2 emissions and does not use moving parts so that its production will last forever [4]. RED converts the free energy Gibbs from the difference in salinity of two solutions [5]. The working principle of RED is shown in Figure 1. RED is a development of ion exchange membrane (IEM) technology. The membrane on RED is arranged alternately between the cation exchange membrane (CEM) and the anion exchange membrane (AEM). The alternating solutions of different salinities are flowed in the space between the membranes (compartments).

RED has an electrode sys-tem consisting of anode, cathode and elec-trode rinse solution (ERS). The anode and cathode are located at the end of the stack and are equipped with a current collector for tap-ping the electric current to the load. The elec-trode rinse solution (ERS) functions as an ion rinse on the electrode, which flows from the anode to the cathode [5] [6].

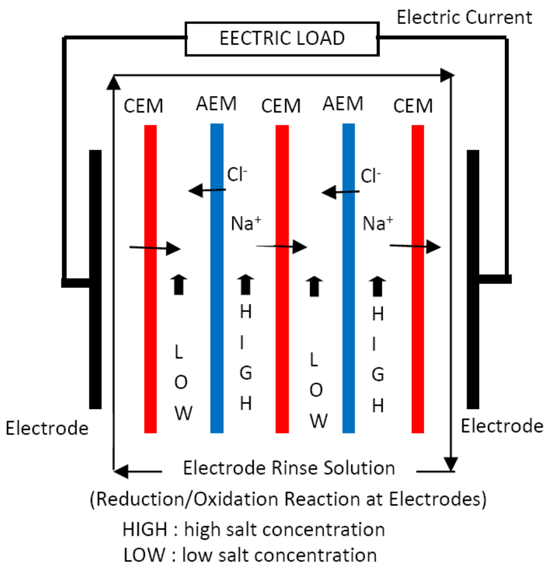

Figure 1. RED Stack Schematic (2 cells)

Meanwhile, many industries in Indonesia that are built on the coast have difficulty in supplying water to operate the plant. To solve the problem, they build a water treatment unit that processes sea water into industrial water or fresh water, this unit is called sea water desalination (SWD). In this process, many technologies are used and the common one is using distillation technology. SWD with distillation technology is an SDW unit that is energy-intensive and has low efficiency, 95% of the seawater as SWD feed becomes blowdown water which is returned to the sea. Because SWD blowdown water has a high enough salinity level, the blowdown water can be converted into electrical energy through RED technology.

With the above background, this article presents an analysis of the use of RED technology on SWD as an effort to mitigate the production of CO_2 emissions.

2. Materials and methods

To analyze the CO_2 emission mitigation at SWD, data is needed which is obtained from the results of reading the operating conditions at an oil refinery in Indonesia that is built near the coast. SWD data includes sea water flowrate, flowrate of water product, energy consumption in the form of electrical energy to run the pump and steam energy to evaporate sea water in the distillation process.

Because SWD energy needs are met from combined heat and power (CHP), data on CHG operating conditions are required including fuel data used, namely residual fuel oil (RFO) flowrate, liquid petroleum gas (LPG) flowrate, electricity product (current, voltage, cos phi), steam product (flowrate, pressure, temperature). To calculate the electric power and steam power from the data obtained, the following equation is used

$$P_{el} = \sqrt{3}.I.V.Cos\theta \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$H = M_{Steam} \,.\, Enthalpi \;\ldots\ldots\ldots\ldots\ldots(2)$$

with P_{el}: electric power (W), I: electric current (Ampere), V: electric voltage (volt), θ : phase angel between electric voltage and current (rad), H: steam energy (J), M_{Steam} : mass of steam (kg), $Enthalpi$: enthalpy of steam (J/Kg).

To calculate the amount of CO_2 emission mitigation in SWD, it begins with calculating the total of CO_2 emission generated by CHG followed by calculating fractional CO_2 emissions. The fractional CO_2 emissions are from electricity products and steam products. The CO_2 emission factors for the electricity product is obtained by dividing the fractional CO_2 emissions of electricity product by the total electricity product. The CO_2 emissions factor for steam product is obtained by dividing the fractional CO_2 emissions for steam product with the total steam product. Electric product and steam product CO_2 emission factors are used to calculate the CO_2 emission in SWD and the amount of CO_2 emission mitigation in SWD with RED.

The total of CO_2 emissions in CHG can be calculated using the emission factor on a stationary engine using the IPCC Tier-1 table with the following equation

$$E_T = F_{Fuel} \,.\, LHV_{Fuel} \,.\, E_F \quad \text{..................} (3)$$

with E_T : total of CO_2 emission ($kgCO_2$), F_{Fuel} : mass of fuel (kg), LHV_{Fuel} : low heating value of fuel (TJ/kg) ,E_F: emission factor of stationer engine (as IPCC Tier-1) ($kgCO_2$/TJ) The CO_2 emission fraction is calculated using the following equation

$$E_H = \frac{H/e_H}{H/e_H + P_{el}/e_P} \,.\, E_T \quad \text{..............................} (4)$$

$$E_T = E_P + E_H \quad \text{..} (5)$$

with E_H: CO_2 emission of steam product ($kgCO_2$), H: power output of steam product (MW), e_H: efficiency of steam product, P_{el}: power output of electric product (MW), e_P: efficiency of electric product, E_T: total of CO_2 emission ($kgCO_2$), E_p: CO_2 emission of electric product ($kgCO_2$).

In this article, the efficiency of the electric product fraction is 35% (US Standard) and for product steam fraction is 80% (US Standard) [7]. CO_2 emission factors for electric products and steam products are using the following equation

$$E_{CO2El} = E_P \,/\, W_{el} \quad \text{..} (6)$$

$$E_{CO2St} = E_H \,/\, W_{st} \quad \text{..} (7)$$

with E_{CO2El} : CO_2 emission factor of electric product ($tonCO_2$/MWh), E_{CO2St} : CO_2 emission factor of steam product ($tonCO_2$/MWh), W_{el}: the electric energy of CHP product (MWh/y), W_{st}: the steam energy of CHP product (MWh/y), E_H: CO_2 emission of steam product ($tonCO_2$/y), E_p : CO_2 emission of electric product ($tonCO_2$/y).

To determine the amount of CO_2 emission mitigation on SWD using RED, the number of Gibbs free energy from blowdown water must be known first. To determine the Gibbs free energy from blowdown water, it is assumed that the blowdown water which has a concentration of 0.616 mol/L as a concentrated solution and river water which is brackish water with a concentration of 0.1 mol/L as a dilute solution and flowrate of blowdown water and river water considered equal [8].

The number of Gibbs free energy is calculated by the following equation [9]

$$\Delta G = 2RT\left[V_L C_L \ln\frac{C_L}{C_M} + V_H C_H \ln\frac{C_H}{C_M}\right] (8)$$

$$C_M = \frac{V_L C_L + V_H C_H}{V_L + V_H} \quad \text{..} (9)$$

with ΔG : free energy Gibbs/s (W), R: gas constants (8,31 J/mol.°K), V_L: dilute flowrate (m^3/s), T: temperature (°K), C_L: dilute concentration (mol/m^3),), V_L: concentrate flowrate (m^3/s), C_L: concentrate concentration (mol/m^3),C_M : mix concentration (mol/m^3).

To get the amount of CO_2 emission that can be mitigated is to multiply the electrical energy generated by RED with the CO_2 emission factor of the electric product generated by CHP. While the electrical energy generated by RED is obtained by multiplying the potential Gibbs energy from mixing two solutions with the generating efficiency of RED. In this article, the RED generator efficiency used is 45.7% [10].

3. Results and Discussion

Sea water desalination (SWD) is a unit that processes sea water into industrial water, clean water and even drinking water. In this article, SWD analysis is used as a unit to supply industrial water for oil processing purposes. There are 8 SWD units, 7 SWD units are operated with a total production of 242 m^3/h with sea water as raw material with a total flowrate of 3,403 m^3/h (see Table 1). The technology used is multi-stage flash distillation technology with 24 stages [11], the working principle of seawater being pumped into the SWD unit and heated using steam which causes seawater to become steam which is then condensed to become industrial water. Not all seawater as SWD feed becomes steam, the remaining water in the SWD process is called blowdown water which is returned to the sea. The SWD with distillation technology is a SWD with very low efficiency, at this SWD, 93% of the water is returned to the sea

To flow raw materials (sea water) to the SWD unit, 8 pumps are used with operating conditions as shown in table 1, while for the distillation process, namely by evaporating seawater, steam is used with operating conditions as shown in table 1. It can calculate if the steam power consumption used is 64.1 MW or the annual steam energy consumption is 561,516 MWh/y and the electric power consumption to run the pump is 0.164 MW or annual electric energy consumption is 1,436.64 MWh/y. The total power used is 64,264 MW or the total annual energy consumption is 562,952,640 MWh/y.

Table 1. Operating point of SWD in oil refinery

No.	Product	Steam			Pump				
UNIT	Flowrate (m^3/h)	Flowrate (Tons/h)	Temp. (Celcius)	Pressure (Kg/cm^2)	Flowrate (Tons/h)	Pressure (Kg/cm^2)	Current (A)	Voltage (Volt)	Cos Phi
SWD 1	27	10	100	0.46	425	2	26	345	0.8
SWD 2	28	10	100	0.46	282	1,9	25	345	0.8
SWD 3	repair	-	-	-	off	-	-	-	-
SWD 4	23	7	115	0.94	450	1,9	146	400	0.8
SWD 5	31	15	105	0.72	425	2,3	30	345	0.8
SWD 6	42	14	113	0.82	575	2,4	29	345	0.8
SWD 7	49	15	112	0.71	671	2,5	35	345	0.8
SWD 8	42	15	111	1.05	575	2,5	30	345	0.8
	242	**86**			**3.403**				

Tabel 2. Capacity and operation condition of Boiler CHP Units

CHP Units	Boiler Capacity (tons/h)	HP Steam			Fuel	
		Flowrate (tons/h)	Pressure (kg/cm^2)	Temp (°C)	Fuel Oil (tons/h)	Fuel Gas (tons/h)
BLR1	60	46,0	62,6	462,7	1,8	0,83
BLR2	60	41,0	62,0	463,2	2,4	0,93
BLR3	60	-	-	-	-	
BLR4	110	69,4	60,9	459,2	5,6	-
BLR5	110	78,0	60,4	462,0	9,9	1,42
BLR6	110	77,0	60,3	465,0	8,5	1,32
BLR7	110	77,5	60,7	461,3	9,6	0,57
BLR8	110	75,5	60,4	464,0	7,1	0,94
Total	**730**	**464,4**	**60,9**	**462,5**	**44,9**	**6,01**

Tabel 3. Capacity and operation condition of Steam Turbine Generator CHP Units

Generator Units	Capacity MW	Electricity			MP Steam		
		Voltage (volt)	Current (ampere)	Cos Phi	Flowrate (tons/h)	Pressure (kg/cm^2)	Temp (°C)
STG1	8	13800	235	0,83	43,9	18.7	370,9
STG2	8	13800	245	0,82	49.9	18.8	371,9
STG3	8	-	-	-	-	-	-
STG4	20	13800	600	0,85	70,0	18.7	360,0
STG5	20	13800	400	0,86	56,0	18.5	345,5
STG6	20	13800	410	0,82	61,0	18.8	350,2
STG7	20	13800	405	0,85	45,0	18.5	352,0
STG8	8	13800	240	0,80	36,0	18.5	348,2
Total	**112**				**361,8**	**18,7**	**356,9**

If we calculate the energy required to produce 1 m^3 of fresh water is 0.246 MWh/m^3. It can be stated that this SWD unit is very wasteful of energy compared to the results of the Humplic et.all (30-90 kWh/m^3)[12]. For this reason, it is necessary to further investigate the cause of the energy leak in this plant.

There are 8 CHP system units with the total boiler capacity is 730 tons/h as shown in Table 2. From the table 2, it shows that the total HP steam product is 464.4 tons/h. The boiler system used fuel oil in the form of RFO (residue fuel oil) and fuel gas in the form of LPG. The total fuel oil consumed in this system is 44.9 tons/h and fuel gas is 6.01 tons/h. By using the LHV value are 39.46 MJ/kg for RFO [13] and 45.5 MJ/kg for LPG [13], the energy consumption of the CHP system from fuel oil is 1,771,754 MJ/h (15,520.57 TJ/y) and from fuel gas is 273,455 MJ/h (2,395 TJ/y).

The total energy consumed is 2,045,209 MJ/h (17,915.57 TJ/y). This Boiler system is used to operate the steam turbine generator with a total capacity of 112 MW (see Table 3). The steam turbine generates electricity with a total power of 50.7 MW equivalent to 444,132 MWh/y and MP steam 361.8 tons/h with an average pressure of 18.7 Kg/cm^2 and an average temperature of 356.9°C.

The steam energy is equivalent with a power of 317 MW (2,776,920 MWh/y). By using IPCC Tier-1, the CO_2 emission coefficients for stationary engines fueled are 77,400 $kgCO_2/TJ$ for RFO [14] and 63,100 $kgCO_2/TJ$ for LPG [14]. The CO_2 emissions produced by the CHP system sourced from fuel oil is 137,133.76 $kgCO_2/h$ (1,201,291,734 $kgCO_2/y$) and those sourced from LPG are 17,255.01 $tonsCO_2/h$ (151,153,892 $kgCO_2/y$) and the total CO_2 emission is 1,352,445,626 $kgCO_2/y$. The CO_2 emission fraction for electric product is 362.056.594 $kgCO_2/y$ and for steam product is 990.389.032 $kgCO_2/y$.

Thus, it is found that the CO_2 emission factor of electric product in CHP system is 815.20 $kgCO_2/MWh$ and steam product is 262.22 $kgCO_2/MWh$. So that the CO_2 emission in the SWD unit is obtained at 1,171,149 $kgCO_2/y$ from electric consumption and 147,240,725 $kgCO_2/y$ from steam consumption. From both, the sum of total CO2 emission is 148,411,874 $kgCO_2/y$.

The potential Gibbs energy generated from the mixing of SWD unit blowdown water with river water or brackish water is obtained. It found that an electric power is 0.905 MW or the energy equivalent is 7,928 MWh/y. With RED, the Gibss energy can be captured to generated electric power of 0.414 MW or the equivalent to electrical energy of 3,626 MWh/y. Therefore, the CO_2 emission that can be mitigated is 2,955,915 $kgCO_2/y$.

The results is very small compared to SWD unit which consumes very wasteful energy. If it is in accordance with the results of the review by Humplik et.all where for SWD with multi stage flash distillation (MSF), to produce industrial water as much as 242 m^3/h or 2,119,920 m^3/y requires energy of 63,597 - 190,792 MWh/y and produces CO_2 emissions of 51,844,274 – 155,533,638 $kgCO_2/y$. Due to the total emission generated by the SWD unit is only able to mitigate CO2 emissions around 1.9 - 5.7%, it shows the result is very small.

More significant results can be obtained if SWD technology is replaced by reverse osmosis technology (SWRO = Sea Water Reverse Osmosis). The energy required to generate 1 m^3 of industrial water at SWRO is around 2 kWh/m^3 with efficiency is 50% [15]. To produce 242 m^3/h (2,119,920 m^3/y) of industrial water, the SWRO takes 484 m^3/h (4,239,840 m^3/y) of sea water and the energy of 4,239.8 MWh/y. The SWRO also produced blowdown water of 242 m^3/h (2,119,920 m^3/y) with a salinity concentration of 68 g/L (assuming 35 g/L seawater and 1 g/L fresh water = 0.5 g/0.5 L, the blowdown water is 34.5 g/0.5 L = 69 g/L (NaCl) = 1.18 mol/L = 1,180 mol/m^3). CO_2 emission produced by this system is 3,456,285 $kgCO_2/y$.

If SWRO blowdown water is converted into electrical energy with RED, it will produce an electric power of 719,6 MWh/y and CO_2 emissions that can be mitigated is 586,618 $kgCO_2/y$. This value is equivalent to 17% of the CO_2 emissions generated by the SWRO system to produce 242 m^3/h of industrial water.

4. Conclusion

Analysis has been carried out to determine the amount of CO_2 emissions that can be mitigated by utilizing RED on the SWD. SWD with multi-stage flash (MSF) technology in the unit used as a case study using wasteful energy consumption and resulting in insignificant mitigation of CO_2 emissions, is therefore suggested to investigate further to look for energy leaks. Mitigation of CO_2 emissions with RED will appear more significant if the SWD technology used is SWRO technology. To increase the amount of CO_2 emission mitigation it is recommended to use SWRO technology to process seawater into industrial water and combine SWRO technology with RED technology for better energy utilization and save the environment.

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