The potential recovery energy of SWD (sea water desalination) by SGP (salinity gradient power)

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Abstract. Fresh water is needed in industrial activities. For these needs sea water is usually used as raw material if the plant is near the sea and far from the river. SWD (sea water desalination) is used to process sea water to fresh water, that is by reducing levels of salinity or reducing levels of total dissolved solid (TDS). There are two technologies in SWD, namely thermal distillation and reverse osmosis (RO) membrane technology. Residual SWD process or also called blowdown water has high salinity levels can be converted into electrical energy through SGP (salinity gradient power). There are two technologies to capture energy from salinity differences, namely PRO (Pressure Retarded Osmosis) and RED (Reverse Electrodialysis). PRO and RED are renewable energy technology, there are no emission, no moving part, abundant availability in nature and can be recycled. In this article, an analysis for SWD of oil refinery is carried out. From the analysis results it is known that the plant uses thermal distillation technology, requires power as 64.25 MW and 3,403 m\textsuperscript{3}/h seawater to produce 242 m\textsuperscript{3}/h freshwater. With SGP, the potential recovery of power gained is 0.786 MW. This recovery potential is still too small when compared to energy requirements of SWD with thermal distillation technology, but if it use RO technology that only requires 3.6-5.7 kWh/m\textsuperscript{3} or 0.87 - 1.40 MW to produce 242 m\textsuperscript{3}/h, a significant impact to saving energy will be obtained.

1. Introduction
The need of water for industrial purposes is quite large and always increasing from year to year [1]. This water is needed for process purposes such as cooling systems and also as feed water for hot steam supply equipment. General specifications needed for this system are water with a low salinity level (freshwater), this is with the aim to reduce the occurrence of scale that can make a deadlock piping system and also reduce the danger of corrosion [2]. To meet this need,

usually by using river water or sea water as feed water. Sea water is processed in water treatment to reduce the amount of salt or minerals. The equipment used to process sea water into fresh water is commonly called sea water desalination (SWD).

There are many technologies used in SWD plants which in essence will produce water that has very low salinity levels as product and also residues with very high salinity levels. Water with high salinity content is residue from the SWD plant will be returned to the sea as wastewater. Energy is needed to operate the SWD plant, including being used to run a pump to drain sea
water to the SWD plant. Energy is also needed for the heating system if using evaporation technology in the SWD plant [3]. Meanwhile, the residu from the SWD plant in the form of brine or blowdown water with high salinity levels can be converted into energy that can be used to substitute the energy needs of the SWD plant, namely by using SGP (Salinity Gradient Power) technology [4].

With SGP, SWD blowdown water will be converted to energy by bringing together high-salinity blowdown water with water that is lower salinity than SWD blowdown. RED (Reverse Electrodiaylsis Power Generation) technology is one type of SGP technology, RED is green energy technology, it’s renewable energy with no emission product and no moving part [5]. On this basis, this paper was made with the aim of reviewing the potential of energy recovery from SWD wastewater with SGP technology.

1.1. Sea Water Desalination

Sea water desalination is a plant that is used to purify or reduce levels of salinity of sea water so that it can be used as fresh water for industrial water or drinking water. The salinity level in sea water is quite high, around 30,000-40,000 mg/L, this can be seen in Table 1 with notation \( \mathcal{T}S \): Typical Seawater, \( \mathcal{E}M \): Eastern Mediterranean, \( \mathcal{A}G \): Arabian Gulf At Kuwait, and \( \mathcal{R}S \): Red Sea At Jeddah [6]. It can be seen from the table that the dissolved solid content (TDS) is quite large, if sea water is directly used as feed water in a piping system such as a boiler system, the mineral content of the sea water will be able to precipitate and clog up the piping system [2]. This stretching is very dangerous because there will be an over-heat system that can make the pipe burst and the danger of explosion. Therefore the content of dissolved solids must be reduced through SWD.

| Constituent       | \( \mathcal{T}S \) | \( \mathcal{E}M \) | \( \mathcal{A}G \) | \( \mathcal{R}S \) |
|-------------------|---------------------|---------------------|---------------------|---------------------|
| Chloride (Cl-)    | 18,980              | 21,200              | 23,000              | 22,219              |
| Sodium (Na+)      | 10,556              | 11,800              | 15,850              | 14,255              |
| Sulfate (SO4+2)   | 2,649               | 2,950               | 3,200               | 3,078               |
| Magnesium (Mg+2)  | 1,262               | 1,403               | 1,765               | 742                 |
| Calcium (Ca+2)    | 400                 | 423                 | 500                 | 225                 |
| Potassium (K+)    | 380                 | 463                 | 460                 | 210                 |
| Bicarbonate (HCO3-) | 140               | -                   | 142                 | 146                 |
| Strontium (Sr-2)  | 13                  | -                   | -                   | -                   |
| Bromide (Br-)     | 65                  | 152                 | 80                  | 72                  |
| Boric Acid (H3BO3)| 26                  | 72                  | -                   | -                   |
| Fluooride (F-)    | 1                   | -                   | -                   | -                   |
| Silicate (SiO3+2) | 1                   | -                   | 1.5                 | -                   |
| Iodine (I-)       | <1                  | 2                   | -                   | -                   |
| Others            | 1                   | -                   | -                   | -                   |
| Total Dissolved Solid (TDS) | 34,483 | 38,6 | 45 | 41 |

To reduce salinity levels, energy is needed depending on the technology used. There are various kinds of technology used in the SWD process including thermal distillation, membrane separation, freezing, electrolydialysis and others. Commercially, distillation and RO (Reverse Osmosis) technology is the most widely used [7].

In distillation technology, the process that occurs is that seawater is heated and evaporation will occur based on the vapor point of each seawater material. Minerals or solids will be left
behind because the vapor point is higher than the fresh water vapor point. The fresh water vapor is then cooled to get the liquid phase through the condenser. The distillation system can produce water with TDS around 1 – 50 mg/L [6]. The remaining material will be blow down as waste water and returned to the sea. High efficiency is obtained if we are able to control the temperature and pressure to separate the solids that are in seawater and fresh water with a low solid content. Energy is used for pumping and heating seawater. The amount of energy required to vaporize a liquid is called the heat of vaporization. For water, this amounts to 2,256 kilojoules per kilogram at 100° C (970 Btu per pound at 212° F) [6].

Not all steam energy is converted to seawater steam, because the thermodynamic laws, steam energy will be lost to heat energy in piping systems and heat transmission in distillation systems. Therefore, to improve the performance and efficiency, the distillation system is developed into several methods such as Multi-stage flash distillation (MSF), Multiple-effect distillation (MED), also it’s developed by utilizing solar energy as a heat source for distillation [8].

![Figure 1: Schematic of a 'once-through' multi-stage flash desalinate](image)

**Figure 1:** Schematic of a 'once-through' multi-stage flash desalinate

RO is one kind of membrane separating technology. RO separates seawater high salinity by using a membrane that is given high pressure so that the solid particles will be left while the water escapes from membrane is water with a low salinity content. The efficiency of the system depends on the type of membrane and the amount of pressure applied. Generally TDS that passes through the membrane is 10 - 100 mg/L [6]. Energy is needed for pumping and give the high pressure to the system. 1: Sea water inflow, 2: Fresh water flow (40%), 3: Concentrate flow (60%), 4: Sea water flow (60%), 5: Concentrate (drain), A: Pump flow (40%), B: Circulation pump, C: Osmoses unit with membrane, D: Pressure exchange [10].

1.2. Salinity Gradient Power (SGP)

Salinity-gradient power (SGP) is a renewable energy, It was mentioned that besides the gravitational potential, the natural run off in coastal areas has a huge physical-chemical potential. This potential is the result of the salinity-gradient between the mainly-fresh run off (river mouths) and the receiving mainly-saline reservoirs (seas and oceans). When a river runs into a sea, spontaneous mixing of fresh and salt water occurs. This natural process is irreversible; no work is attained from it. However, if the mixing is done (partly) reversibly, work can be obtained from the mixing process [11].
If two different solutions of salinity are mixed, there will be energy released, this energy is usually referred to as Gibbs free energy. For monovalent pure salt solutions and relatively low saline concentrations, Gibbs free energy from liquid mixing for low concentration of salt solution (volume $V_L$ in $m^3$, and concentration $C_L$ in $mol/m^3$) and high concentration salt solution (volume $V_H$ in $m^3$, and concentration $C_H$ in $mol/m^3$) stated with:

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

with

$$C_M = \frac{V_L C_L + V_H C_H}{V_L + V_H} \text{ (mol.m}^{-3}\text{)}$$

$C_M$ is the final concentration of the solution after mixing, $R$ is gas constant as 8,314 J/mol.$^\circ$K, $T$ is temperature in Kelvin degree.

Ricard Pattel is a scientist who states that the mixing of sea water and river water can be used as a source of electrical energy through "hydroelectric pile". In 1954 it stated: "The osmotic pressure of seawater is 20 atmospheres so that if river water and sea water mix, there will be energy loss equivalent to the energy produced from falling water as high as 680 ft" [12]. The global energy potential of mixing sea and river water as an energy source is huge. Every cubic meter of river water can produce 1.4 MJ of energy if mixed with sea water with the same amount (assuming a salinity concentration of 30 $^{0/00}$) and more than 2 MJ if mixed with more seawater. The potential energy produced globally with SGP technology (2.7 TW) will exceed to the global energy needs (2 TW) [13].

There are two membrane-based technologies that are currently being developed to capture energy from mixing liquids with different salinity, namely pressure retarded osmosis (PRO) and reverse electrodialysis (RED).

1.3. Pressure Retarded Osmosis (PRO)
Pressure retarded osmosis system is the reverse of the reverse osmosis process, where if two saline-different solutions are mixed through a semipermeable membrane the lower salinity solution will flow to a higher salinity solution. The high salinity level stream flow the greater flow solution. The transport of water from the low pressure diluted solution to the high-pressure concentrated solution results in a pressurization of the volume of transported water. This flow can be used to
drive a turbine generator to produce electrical energy. RO requires energy to fight the osmosis process, whereas PRO captures energy from the osmosis process. The combination of RO and PRO can improve efficiency in desalinators where PRO can recover the energy needed by RO [14].

Q is the volumetric solution flow (m$^3$/s), $\Delta Q$ the transported amount of water in time through the membranes (m$^3$/s), $\Delta P$ the applied hydrostatic pressure difference between both solutions (Pa), whereas the power generated by means of a turbine and generator is $\Delta Q \cdot \Delta P$ (W) [15].

1.4. Reverse Electrodialysis (RED)
Reverse electrodialysis (RED) is a technology to generate electricity from the salinity difference between two solutions, e.g. seawater and river water. RED is the opposite of ED (electrodialysis), if ED requires energy to separate particles, RED produces energy from ion separation. The principle of RED is illustrated in Fig. 3. A RED system is composed of ion exchange membranes and compartments for seawater and river water (in alternating order). The ion exchange membranes are selective for either cations or anions. Membrane functions to pass the ion, negative ions will be passed by the cation exchange membrane (CEM) while the positive ion will be passed by anion exchange membrane (AEM). NaCl salt solution (sea water) consists of Na$^+$ ions and Cl$^-$ ions, if NaCl solution from seawater and H$_2$O or fresh water from river water is included in the compartment in which there is a CEM and AEM membrane then each compartment will produce a potential difference. Multiple cells inside the compartment can be arranged serially to produce a large potential difference. At the end of the membrane circuit is attached electrode as tapping the potential difference to be connected with the electrical load in order to occur the flow of electric current to outside equipment. At the electrode occurs reduction and oxidation reactions (redox) [16–18].

1.5. Potential of Recovery Energy on SWD in Oil Refinery Plant : Case Study
In this section, we will discuss the potential of energy recovery in SWD at one of the oil refinery plants in Indonesia. In this oil refinery SWD has been installed with total capacity of 540 m$^3$/h with pump installation with total capacity of 6,320 m$^3$/h. The technology its used in this plant is distillation technology. The installed capacity is realized in 8 SWD units with 8 pump units as shown in table 2. In table 2 presents data on SDW operating points relating to SWD production results and data related to energy consumption. There are 8 units installed, there is one unit that is in maintenance condition

Table 2. Operating point of SWD plant in oil refinery plant
There are two power sources used in this SWD unit, namely steam and electric pump. To calculate the power consumption derived from steam, the following equation is used with \( U \) is energy in kJ, \( m \) is mass in kg and \( h \) is specific enthalphy,

\[
U = mh
\]  
\[(3)\]

The specific enthalpy of steam can be obtained through the steam properties table whose value depends on the amount of pressure and temperature of the steam. Currently the steam properties table has been created in the form of a downloadable application [19]. The specific enthalphy steam values in the SWD in this report can be seen in Table 3. To calculate the power consumption of the pump, a three-phase electric power equation is used, because the pump drive is a three-phase electric motor, expressed by the following equation

\[
P = \sqrt{3}VI\cos\theta
\]  
\[(4)\]

with \( P \) is power in Watt, \( V \) is voltage in volt, \( I \) is current in ampere, is phase angel in radian. The energy calculation needed to produce 242 m\(^3\)/h is shown in table 3, which is 64,261 MW with seawater intake of 3,403 m\(^3\)/h. It can be seen that to produce freshwater from seawater by using distillation technology in this plant is needed 0.265 MWh/m\(^3\). If it’s compared with the results of previous researchers who stated that the power consumption in SWD with MSF distillation
technology is around 23.9 - 96 kWh/m$^3$ [20], this SWD plant is very wasteful. Therefore, it is necessary to further investigate the energy leak that occurred. These results show that the use of thermal distillation technology requires more energy compared to RO technology which only requires as much energy 3.6-5.7 kWh/m$^3$ [20–22].

Table 3: Power consumption of SWD unit

| SWD Unit | Flowrate (Tons/h) | Steamer Entalphy (kJ/kg) | Power (kWatt) | Pump Flowrate (m$^3$/h) | Power (kWatt) |
|----------|------------------|--------------------------|-------------|------------------------|-------------|
| 54WS-1   | 10               | 2,669.01                 | 425         | 12.43                  |
| 54WS-2   | 10               | 2,669.01                 | 282         | 11.95                  |
| 54WS-3   | -                | -                        | -           | -                      |
| 54WS-201 | 7                | 2,695.61                 | 450         | 80.92                  |
| 054WS101 | 15               | 2,676.29                 | 425         | 14.34                  |
| 054WS102 | 14               | 2,692.70                 | 575         | 13.86                  |
| 054WS103 | 15               | 2,691.89                 | 671         | 16.73                  |
| 054WS105 | 15               | 2,685.20                 | 575         | 14.34                  |
| Total    | 86               | 64,096.66                | 3,403       | 164.58                 |

To calculate the potential of energy from salinity difference in the SWD, based on equation 1, it is necessary to calculate the concentration of seawater intake, product and blowdown water. We assume the seawater intake concentration is the same as the typical sea water concentration in table 1 while the product concentration is assumed to be 100 mg/L.

Table 4: Concentration of seawater and SWD product

| Ar  | Sea Water (SWD Intake) (mg/L) | Product (mol/m$^3$) (mg/L) |
|-----|-------------------------------|-----------------------------|
| Cl  | 17 18,980.00                   | 55.23 3.25                  |
| Na  | 11 10,556.00                   | 30.72 2.79                  |
| SO4 | 48 2,649.00                    | 7.71 0.16                   |
| Mg  | 12 1,262.00                    | 3.67 0.31                   |
| Ca  | 20 400.00                      | 1.16 0.06                   |
| K   | 19 380.00                      | 1.11 0.06                   |
| HCO3 | 31 140.00                     | 0.41 0.01                   |
| Total | 34,367.00                   | 2,280.98 100.00             | 6.64         |

Assuming all SWD products can be collected again and brought together with water blowdown, based on equation 1, the potential power can be reach as 0.786 MW. This value is still too small when compared to the power needed by SWD with distillation technology, it’s around 5.78 – 23.23 MW, if the SWD uses RO technology, it’s needed energy around 0.87 – 1.40 MW, the potential power recovery will provide a fairly good impact in energy savings.

2. Conclusion

Fresh water is very necessary for industrial activities. To meet the needs of fresh water in the industry required sea water desalination. Seawater desalination is a technology of purifying sea water into fresh water by reducing salinity levels through the distillation process or also through the reverse osmosis process. SDW waste in the form of high-salinity water blowdown can be recovered to become energy through SGP (salinity gradient power). There are two
Table 5: Calculation of SWD Blowdown concentration

| SWD Unit  | Intake Flow (m$^3$/h) | Intake (gr/h) | Product Flow (m$^3$/h) | Product (gr/h) | Blowdown Flow (m$^3$/h) | Blowdown (gr/h) | Concentr (mol/m$^3$) |
|-----------|----------------------|---------------|------------------------|----------------|------------------------|----------------|-------------------|
| 54WS-1    | 425                  | 14,605,975    | 27                     | 2,700          | 398                    | 14,603,275    | 2,435.47          |
| 54WS-2    | 282                  | 9,691,494     | 28                     | 2,800          | 254                    | 9,688,694     | 2,531.90          |
| 54WS-3    | off                  | repair        | -                      | -              | -                      | -             | -                 |
| 54WS-201  | 450                  | 15,465,150    | 23                     | 2,300          | 427                    | 15,462,850    | 2,403.68          |
| 054WS101  | 425                  | 14,605,975    | 31                     | 3,100          | 394                    | 14,602,875    | 2,460.12          |
| 054WS102  | 575                  | 19,761,025    | 42                     | 4,200          | 533                    | 19,756,825    | 2,460.39          |
| 054WS103  | 671                  | 23,060,257    | 49                     | 4,900          | 622                    | 23,055,357    | 2,460.35          |
| 054WS105  | 575                  | 19,761,025    | 42                     | 4,200          | 533                    | 19,756,825    | 2,460.39          |
| Total     | 3,403                | 242           |                        |                |                        |                | 2,455.30          |

technologies currently being developed to capture energy through SGP, namely pressure retarded osmosis (PRO) and reverse electrodialysis (RED). From the results of the analysis of SDW with distillation technology in oil refineries, the power used is quite large and wasteful, so it needs reinvestigation related to the use of energy in SWD. The recovery from SWD waste becomes energy that is too small for the energy consumption in the distillation process, but if it compared to the SWD energy usage that uses RO technology, the energy recovery is still quite satisfying.

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