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Harnessing Ocean Alkalinity Enhancement (OAE) for CO_2 Decomposition and Renewable Energy Production : The AODOP Innovation Towards Net-Zero Emissions 2060

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ABSTRACT
As the concentration of carbon dioxide (CO_2) in atmosphere increases, carbon emissions entering the oceans have become a significant concern in context climate change studies as stated by the Intergovernmental Panel on Climate Change (IPCC) report, 30% of anthropogenic CO_2 emissions are absorbed by the oceans, leading decrease in ocean pH and harmful impacts on marine ecosystems. In order to address this challenge, Ocean Alkalinity Enhancement (OAE) has emerged as a promising strategy. By using calcium carbonate compounds, OAE aims to increase seawater alkalinity and enhance its capacity to decompose CO_2. The practical implementation of OAE until now is still under further research. Therefore, the initial stage of this application will be carried out in a storage tank as an initial trial before being applied on a large scale. Furthermore, the results of the OAE process can contribute to production of renewable energy through the implementation of Pressure Retarded Osmosis (PRO) technology, which leverages the salinity gradient between seawater with high alkalinity and freshwater to generate energy. By combining OAE with PRO this approach offers a promising pathway toward a thriving blue future to facilitate the integration of marine ecosystems in achieving sustainability and net-zero emission by 2060.

Keywords: *Carbon dioxide (CO_2), Ocean Alkalinity Enhancement (OAE), Pressure Retarded Osmosis (PRO), Renewable energy, Net-zero emissions.*

1. INTRODUCTION

1.1 Backgound
Elevated levels of atmospheric CO_2 have had significant negative impacts on marine ecosystems. Global Carbon Budget reports data on Carbon dioxide (CO_2) emissions from fossil fuels and industry showing that by 2022 there had been 728.88 million tons of emissions and there had been an increase from the last 10 years. As a result, this affects the phenomenon of ocean acidification due to high concentrations of dissolved CO_2. This acidification occurs as a result of carbon emissions dissolved in the ocean, with the Intergovernmental Panel on Climate Change (IPCC) reporting that 30% of anthropogenic CO_2 emissions have been sequestered by the oceans, polluting marine ecosystems. These impacts are a major concern in climate change studies because they threaten the viability of marine ecosystems, such as a decrease in pH that disrupts the calcification process of marine organisms, including corals and molluscs, and affects the overall marine food chain.

In light of these challenges, it is imperative to develop an innovative solution that not only addresses the adverse effects of carbon emissions but also supports the attainment of net-zero emissions by 2060. One potential solution is the application of Ocean Alkalinity Enhancement (OAE) using calcium carbonate compounds, which has been identified as a promising approach to reducing CO_2 concentrations in the ocean. Currently, the application of OAE is still in the research stage and has not been widely applied as a strategy for reducing CO_2 in the ocean. Therefore, the development of innovative measures is needed. To prove the efficacy of reducing carbon emissions in seawater, preliminary trials were conducted using OAE in a closed system with a specified capacity as an initial step before full application in the ocean. Therefore, the main objective of this study was to assess the efficacy of OAE by initial testing using a storage tank before being applied on a large scale.

In addition to its role in reducing carbon emissions, seawater can also be harnessed as a source of renewable energy. One potential avenue for exploration is the electrolysis of seawater, which has the potential to produce hydrogen (H_2) as renewable energy. An alternative option to utilize seawater with elevated alkalinity, can be obtained from the OAE process to become renewable energy through the Pressure Retarded Osmosis (PRO) method. Pressure Retarded Osmosis (PRO) technology employs the salinity differential between seawater and freshwater via a semipermeable membrane to generate osmotic pressure, which can then be transformed into kinetic energy through a turbine and subsequently into electrical energy. The energy produced by this pressure differential is referred to as osmotic or salinity energy.

In order to construct a prosperous blue future, it is essential to leverage innovative technologies by combining OAE and PRO to facilitate the generation of renewable energy. By employing the principle of kinetic energy generation through the utilization of pressure-driven osmosis and combine with the application of OAE to enhance seawater alkalinity, this approach can facilitate the integration of marine ecosystems in achieving sustainability goals and contribute to the realization of the net zero emission target by 2060. Therefore, JNS's team present AODOP innovation, as a solution which a technology that applies the Alkalinity Ocean to Drive Osmotic Power (AODOP) for produce the energy where seawater with high alkalinity is processed through OAE with Pressure Retarded Osmotic (PRO) technology to create renewable energy.

1.2 Research Area

The Java Sea significantly contributes to the increase in CO_2 emissions from the ocean to the atmosphere. The shallow areas, influenced by high temperatures and low salinity, trigger the transfer of CO_2 to the atmosphere. This region shows a notable Δp CO_2 value, reaching approximately 100 µatm, which is much higher compared to other areas like the Flores and Banda Seas, where the difference is only around 40 µatm. Additionally, the average SSpCO_2 recorded in the Java Sea during the observation period was 388.3 ± 16.4 µatm, which is higher than the mean atmospheric CO_2 concentration of 376.3 ± 2.9 µatm.[1]

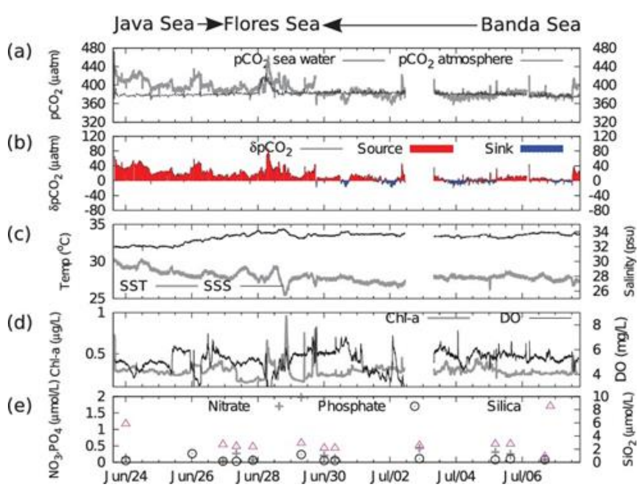


Figure 1. Variations in oceanographic parameters in the waters between the Java Sea and the Flores-Banda Sea over a certain period of time. [1]

1.3 Paper Objective

The objective of this paper is to achieve net-zero emission by implementation of Ocean Alkalinity Enhancement (OAE) by combining Pressure Retarted Osmosis (PRO) to maximize the potential of the ocean and create renewable energy to become a sustainable marine environment.

2. BASIC THEORY AND METHODOLOGY

2.1 Overview Ocean alkalinity Enhancement (OAE)

Ocean Alkalinity Enhancement (OAE) is a method designed to mitigate the effects of increased concentrations of atmospheric carbon dioxide (CO_2) dissolved in waterand reduce acidification by increasing seawater alkalinity [2]. The addition of alkaline compounds to seawater facilitates the absorption of CO_2 from the atmosphere. This alkalinity addition process converts dissolved CO_2 into bicarbonates and carbonates, which can neutralize the acidity of seawater. Commonly used alkaline substances include calcium carbonate ($CaCO_3$), magnesium hydroxide($Mg(OH)_2$), and calcium hydroxide ($Ca(OH)_2$) [3].

Various methods have been developed to implement OAE where each method has its own advantages and challenges, both in terms of effectiveness and economic feasibility. These methods include the production of alkalinity through the utilization of electrochemical processes, the addition of lime to the sea surface, and the addition of minerals to the seafloor or coastal areas.

In this study, the OAE method used is the addition of alkaline calcium carbonate ($CaCO_3$) compounds, which have the potential to further enhance CO_2 absorption. The particle size of the alkaline compound has a significant impact on the rate of dissolution and its distribution in seawater. The dissolution rate is directly proportional to theparticle size of the compound, with smaller particles exhibiting a higher dissolution rate and a greater potential for distribution in the seawater column. In smaller areas, such as the water column, the grain size required to preventcomplete sinking is less than 1 µm. In larger areas, such as the seafloor, the optimum grain size required is between 0.2 and 1.4 m. The selection of grain size is contingent upon not only the dimensions of the designated area but also the characteristics of the deployment region, which is classified into low- and high-energy environments. In low-energy environments, the surface area is greater, necessitating a smaller grain size, ranging between 20 and 100 µm. In contrast, high-energy environments are characterized by rapid or turbulent water mass movements,necessitating a larger grain size [4].

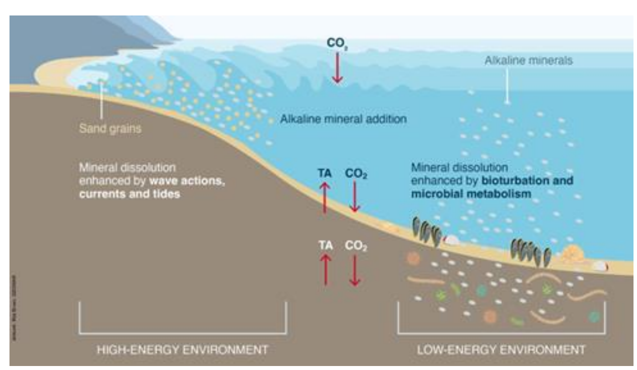


Figure 2. Mineral distribution in Environments with Regional Advantages [4]

2.2 Alkaline Compound and Reaction of OAED

To implement Ocean Alkalinity Enhancement (OAE), an alkaline compound is used to break down CO_2 in the ocean. The alkaline compound used in this case is calcium carbonate. Calcium carbonate ($CaCO_3$) is an inorganic mineral obtained from the suspension of hydrated lime in water and gas [5]. Calcium carbonate is the main component of limestone, chalk, and the exoskeletons of marine animals, including corals and clams. In the presence of water that has undergone carbonation, calcium carbonate will perform a chemical reaction that forms carbonate ions. The reaction can be expressed as follows [6]:

$$CaCO_{3(s)} + CO_{2(g)} + H_2O_{(l)} \rightarrow Ca^{2+}_{(aq)} + 2HCO_{3}^{-}{}_{(aq)}$$

The addition of carbonate can increase the alkalinity level of seawater, maintaining a pH of 8.0. In natural seawater, alkalinity varies between 6.2 and 8.2 dKH, depending on the location. dKH (Degree of Carbonate Hardness) is a measurement of the sufficient amount of carbonate in water to maintain pH stability [7].

2.3 Overview Pressure Retarded Osmosis

In this experiment, the application of OAE to seawater willbe tested at a certain capacity using a container such as a storage tank. To increase the alkalinity of the seawater by reducing the CO_2, calcium carbonate will be spread. The application of Ocean Alkalinity Enhancement (OAE), which increases the alkalinity of seawater, presents a potential avenue for utilizing seawater as an alternative source of renewable energy. One technology that can be applied is pressure-retarded osmosis (PRO), which has the potential to generate electrical energy through the utilization of osmotic pressure [8]. PRO technology functions by leveraging the salinity disparity between seawater and freshwater. The osmotic pressure derived from this contrast in salt concentration is then transformed into energy. Based on the high salinity of water from different sources, it is known that the maximum energy from different sources adapted from Helfer, 2015 showing the following data:

Table 1. Data of Maximum Energy from Various Water [9]

	Theoritcal Energy (kWh/m³)	**Theoretical Power (MW (m³/s)**
Fresh Water	0,3	1,2
Sea Water	0,75	2,7
SWRO Brine	1,5	5,4
Salt-dome Solution	8,8	31,6
Great Salt Lake	10,4	37,5
Dead Sea	14,1	50,7

Therefore, from the utilization of salinity differences for the application of pressure retarded osmosis in order to realize net-zero emissions by reducing CO_2 in the sea, based on the data it is shown that seawater with high salinity can be mixed with low salinity water, thus creating a salinity gradient which forms a pressure later in the pressure retarded osmosis process. Therefore, to implement this difference in salinity, seawater will be utilized by implementing the PRO principle which will be collaborated with the utilization of fresh water obtained from pumping groundwater so that the application of PRO can take place properly. The illustration of the application of the Pressure Retarded Osmosis (PRO) method is as follows.

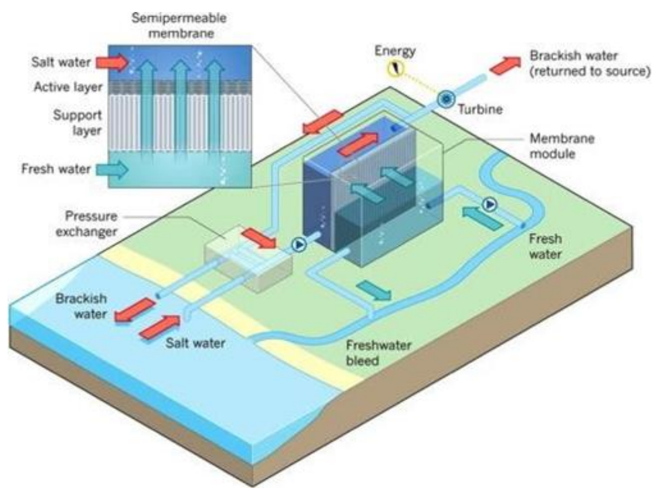


Figure 3. An Application of Pressure Retarded Osmosis[10]

As the illustration shows, the process using a semi-permeable membrane which is utilized in the PRO system permits the passage of freshwater molecules (H_2O) into seawater, while retaining salt ions such as sodium (Na^+) and chloride (Cl^-). As fresh water passes through the membrane, an increase in volume and pressure is observed on the seawater side due to the difference in salt concentration. The resulting osmotic pressure is employed to drive a turbine, which then converts osmotic energy into kinetic energy. This is subsequently transformed into electrical energy through a generator.

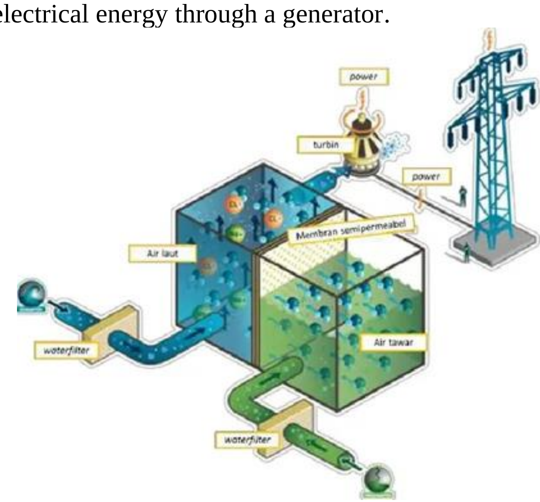


Figure 4. A Process of Pressure Retarded Osmosis [9]

The efficacy of PRO technology is contingent upon the salinity gradient. An increase in the disparity between the salt concentrations of seawater and freshwater will result in a proportional rise in osmotic pressure, thereby enhancing the potential energy that can be derived.The osmosis process thus directly affects the system's ability to generate energy in an efficient manner.

The potential for utilizing the salinity differential between seawater and freshwater as a sustainable, renewable energy source is a significant aspect of PRO technology. The use of semi-permeable membranes that are selective to water molecules ensures that the osmosis process is optimized. The resulting osmotic energy contributes to the development of green energy, thereby making PRO a promising solution in supporting future renewable energy and sustainability targets.

2.4 Generator

The osmotic pressure difference in PRO (Pressure Retarded Osmosis) is capable of generating kinetic energy with the help of a turbine. The energy can be converted into electrical electrical energy using a generator. Generator is a device that functions to convert kinetic energy into electrical energy through a process known as electromagnetic induction. The fundamental principle behind the operation of a generator is that when a conductor, such as a copper wire, moves within a magneticfield, an electric current is induced in the conductor. The generator is equipped with magnets—either permanent or electromagnets—that create the magnetic field necessary for this process**.**

There are two main components inside the generator: the rotating rotor and the stationary stator. As the rotor rotates, it passes through the magnetic field generated by the stator, leading to an increase in magnetic flux and the production of usable electric current. The following serves to illustrate the concept of magnetic flux and the fundamental operational principle of a generator.

Figure 5. The Main Components of Generator [11]

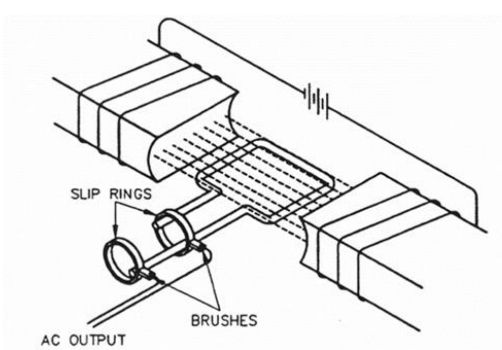


Figure 6. The Principle of Generator [11]

3. RESULT

3.1 AODOP Innovation

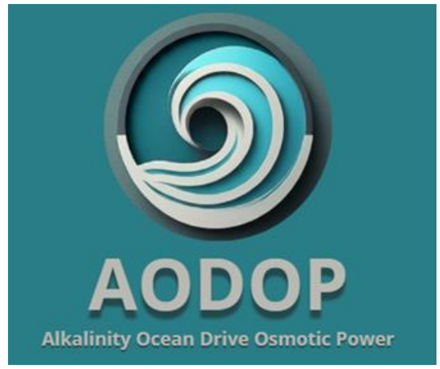


Figure 7. AODOP Innovation

In order to achieve net-zero emissions by 2060, the Innovation of Alkalinity Ocean to Drive Osmotic Power (AODOP) enhancement was developed with the objective of reducing the continuous increase in carbon emissions. The initial focus of this experiment will be on the Java Sea area, where it has been established that Java Sea plays a significant role in the increase of CO_2 emissions from the ocean to the atmosphere. Further development and implementation of this approach will be contingent upon the ability to provide a greater positive impact.

Alkalinity Ocean Drive Osmotic Power (AODOP) employs the Ocean Alkalinity Enhancement (OAE) process in conjunction with Pressure Retarded Osmosis (PRO) technology. The resulting system utilizes the principle of turbines to generate renewable energy from the combined output of these two processes. By spearheading a collaborative endeavor to leverage innovation and technology for sustainable progress, AODOP can serve as a solution to existing problems, contributing to the development of a thriving blue future. The process of applying this AODOP is initiated with the application of OAE. The objective is to reduce CO_2 in the sea, which is achieved by adding an alkaline compound in the form of calcium carbonate. This compound is capable of breaking down CO_2 in the sea by increasing the alkalinity of seawater. However, due to the vastness of the Java Sea, which is the subject of the experiment, and the fact that OAE is still in the research phase and has yet to be applied directly in Indonesia, a preliminary test will be conducted on a limited scale using a container in the form of a storage tank. The AODOP application commences with the pumping of a specified volume of seawater into a storage tank, followed by the introduction of an alkalinity compound, specifically carbonate compounds, which are then tested with a Water Quality Detector. Once this has been completed, the high alkalinity water is employed for the treatment of fresh water, which is also pumped, in order to facilitate a reaction within a semipermeable membrane container. The membrane will then be subjected to pressure-retarded osmosis, which exploits the disparity in salinity between seawater and freshwater. Freshwater molecules will permeate the membrane and migrate towards the seawater side due to the osmotic gradient, which is the difference in salt concentration. This results in an increase in volume of water on the seawater side, leading to an elevated pressure. This pressure is then directed to a turbine, where it is converted into mechanical energy through the generation of pressure. The rotating turbine is then connected to a generator to convert mechanical energy into electrical energy. While the impact provided is not yet significant, further development on a large scale could make this AODOP a viable source of energy while reducing CO_2 in the sea.

3.2 Methodology of the Process

The following flowchart presents the implementation process of the AODOP innovation :

Table 2. Application Method of AODOP in General

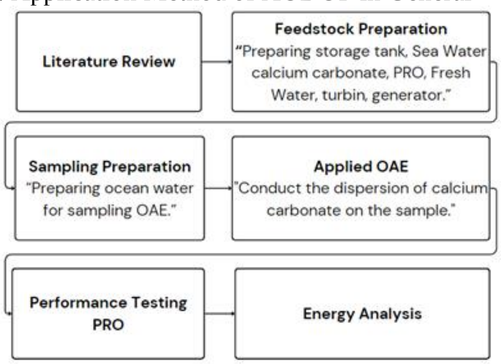


Table 3. Ocean Alkalinity Enhancement Process

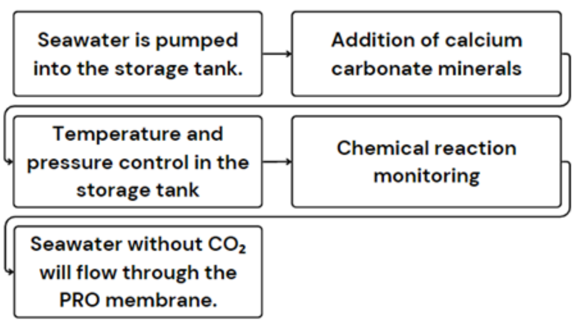
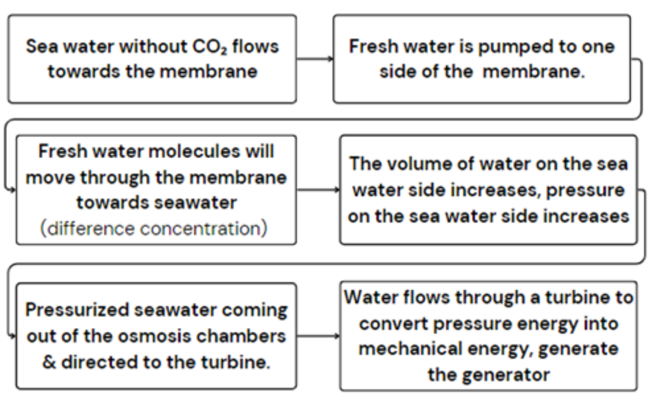


Table 4. Pressure Retarded Osmosis Process



In the initial stage of the OAE process, the seawater to be reacted is pumped from the Java Sea source into a storage tank. The temperature in the tank is maintained at a level approximating the natural temperature of seawater, which is around 20-30°C, and a pressure of 1 atm, which is equivalent to atmospheric pressure. After the seawater is stored in the tank, the mineral substance calcium carbonate in powder form is added to the storage tank to accelerate the dissolution process. The reaction of calcium carbonate ($CaCO_3$) with seawater involves the absorption of carbon dioxide (CO_2), resulting in the formation of bicarbonate ions and an increase in the alkalinity of the seawater. To ensure optimal results, the pH and alkalinity levels of the seawater in the tank are monitored regularly throughout the process. The seawater from the OAE process is then pumped to the semi-permeable membrane in the PRO process referring to table (4).

3.3 Renewable Energy

The objective of this innovation is to facilitate the generation of renewable energy. The Ocean Alkalinity Enhancement (OAE) process, which increases alkalinity in seawater, can be employed as a source of electrical energy through Pressure Retarded Osmosis (PRO) technology. In order to achieve the net-zero emission target by 2060, it is essential to pursue the development of this renewable energy technology. Pressure Retarded Osmosis (PRO) is one such technology that offers significant potential for energy production through the utilization of osmotic pressure, derived from the salinity differential between seawater and freshwater. This technology offers a sustainable solution by leveraging abundant seawater resources and plays a role in reducing global carbon emissions. The principle of osmotic pressure differences in PRO (Pressure Retarded Osmosis) can be utilized to create kinetic energy, which can be harnessed by a generator to drive the turbine. The energy can then be converted into electrical energy using a generator. A generator is a device that facilitates the conversion of kinetic energy into electrical energy through the phenomenon of electromagnetic induction. Therefore, the creation of renewable energy is made possible by the application of this innovation.

3.3 Challenges and Opportunities

In the process of developing this AODOP innovation, it is important to consider the potential opportunities and challenges that may arise in the pursuit of achieving net-zero emissions by 2060. The potential benefits of AODOP implementation include the reduction of CO_2 emissions through the optimization of OAE and PRO synergies, the advancement of renewable energy generation, the development of a sustainable blue economy, and the diversification of energy sources to diminish reliance on fossil fuels. In terms of potential barriers to implementing this AODOP innovation, these may include geopolitical, permitting, and regulatory barriers, high costs and infrastructure requirements, uncertain maintenance requirements, the maturity and resilience of this AODOP in the face of unforeseen environmental consequences that could impact the marine ecosystem.

3.4 Result

Calcium carbonate in the Ocean Alkalinity Enhancement (OAE) system can increase ocean alkalinity and influence changes in pH, calcite saturation, and the relative calcification rate across various ocean regions. The pH of seawater can rise to 9, calcite saturation ($\Omega CaCO_3$) can reach up to 15, and relative calcification can reach a value of 1. Regions with higher alkalinity tend to experience reduced ocean acidification, particularly in non-equilibrated areas with the atmosphere, such as the North Atlantic. Carbonate organisms, such as coral reefs, will benefit from these conditions due to increased calcification.

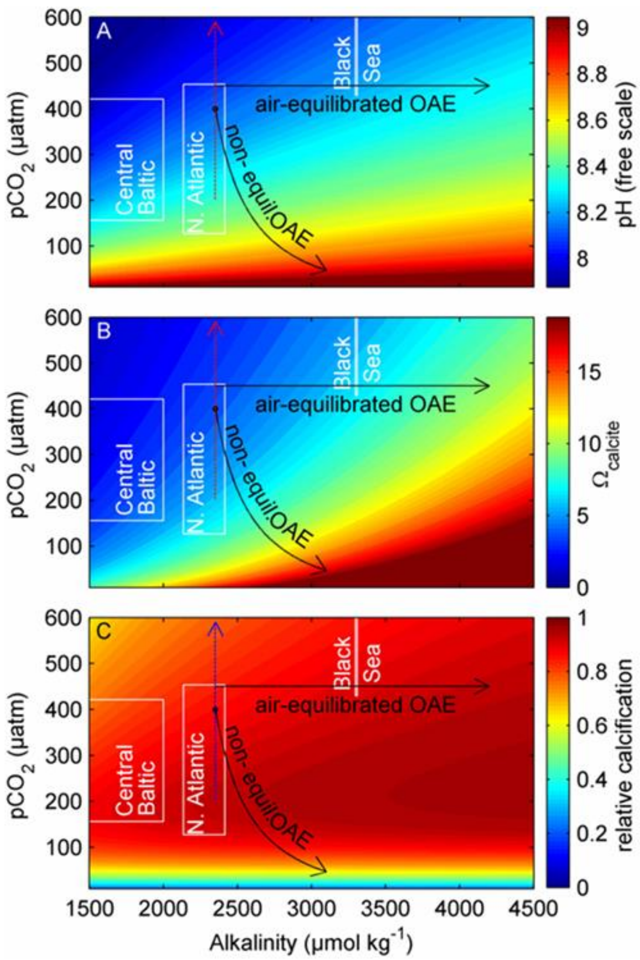


Figure 8. Carbonate chemistry perturbation through EW/OAE [12]

The energy produced by Pressure Retarded Osmosis (PRO), when converted through a generator, can theoretically reach up to 0.75 kWh m^{-3} for seawater with a power of 2.7 $(m^3/s)^{-1}$. However, due to the lack of research in this field, the actual results have not yet been definitively measured [9].

3.5 Economical Analysis

Table 5. Economics Analysis

Parameter	Qty	Unit Price	Total Price
CAPEX			
Material Cost			
Calcium Carbonate (per kg)	6.75	Rp6,000	Rp40,500
Membrane Semipermeable (per unit)	1	Rp350,966	Rp350,966
Processing Cost			
Pump	4	Rp2,850,000	Rp11,400,000
Storage Tank	1	Rp1,300,000	Rp1,300,000
Turbine Generator	1	Rp1,235,500	Rp1,235,500
OPEX			
Energy Cost			
Electricity (kWh)	35040	Rp1,115	Rp39,060,490
Labor Cost			
Worker's Salary	9	Rp1,250,000	Rp11,250,000
Employee's Salary	3	Rp3,000,000	Rp9,000,000
Other Cost			
Maintenance Cost	1	Rp2,000,000	Rp2,000,000
Distribution Cost	1	Rp2,000,000	Rp2,000,000
Indirect Manufacturing Cost			
Water Quality Detector	1	Rp554,600	Rp554,600
Total Cost	**Rp78,192,056**		
Modal per Unit	**Rp9,774,007**		

Capital Expenditures (CapEx) are funds used by companies as initial investments to initiate or expand business projects. These funds include expenditures to gain, improve, and maintain physical assets, including property, plant, buildings, technology, and equipment [13]. In the implementation of AODOP innovation, CapEx includes the cost of purchasing machinery, equipment, raw materials, and prototype development. Operational Expenditures (OpEx) are the costs incurred by a company to maintain its day-to-day operations.

These costs include expenses for rent, equipment, inventory, marketing, payroll, insurance, and funds allocated for research and development [14]. In the implementation of AODOP innovation, OpEx includes electricity costs, labor costs, and equipment maintenance costs. These economic calculations and estimations are based on CAPCOST 2017 program with adjusting to the latest 2024 CEPCI (Chemical Engineering Plant Cost Index) combined with several price estimations from different marketplaces.

To determine the mass of calcium carbonate required to achieve an optimum seawater alkalinity target of 150 ppm [15] at a tank volume of 90 m^3, the following calculations were conducted. Based on the reaction of calcium carbonate with seawater and carbon dioxide, $CaCO_{3(s)} + CO_{2(g)} + H_2O_{(l)} \rightarrow Ca^{2+}{}_{(aq)} + 2HCO_3{}^{-}{}_{(aq)}$, it was determined that an increase in alkalinity of 1.5 mol/m³ necessitates the addition of 0.75 mol³ of $CaCO_3$ where the molar mass of calcium carbonate Mr_{CaCO_3}= 100 g/mol. Calculations are then required to determine the amount of calcium carbonate needed.

$$n_{CaCO_3} = M_{CaCO_3} \times V_{CaCO_3} \qquad (1)$$

$$n_{CaCO_3} = 0.75\ mol/m^3 \times 90\ m^3 = 67.5\ mol$$

Thus, the mass of calcium carbonate is obtained as follows

$$mass_{CaCO_3} = n_{CaCO_3} \times Mr_{CaCO_3} \qquad (2)$$

$$mass_{CaCO_3} = 67.5\ mol \times 100\ g/mol = 6{,}750\ g$$

$$mass_{CaCO_3} = \ 6.75\ kg$$

4. CONCLUSION

AODOP (Alkalinity Ocean to Drive Osmotic Power) is a solution to reduce rising CO_2 emissions and promote sustainable energy generation in order to achieve net-zero emission targets by 2060. This innovation combines the Ocean Alkalinity Enhancement (OAE) method with Pressure Retarded Osmosis (PRO) technology to generate osmotic energy that can be converted into electrical energy. The research focuses on the Java Sea, which has substantial CO_2 emissions due to rising temperatures and low salinity. Due to the fact that there is no definite application of OAE, the study methodology includes small-scale testing in seawater storage tanks where alkaline compound is added to increase alkalinity before being delivered to the PRO system.

The findings show that the OAE method can increase seawater alkalinity in combination with PRO technology that has the potential to generate considerable osmotic energy. While currently on a modest scale, these innovations have the potential to significantly reduce CO_2 emissions by spearheading a collaborative endeavor to leverage innovation and technology for sustainable progress. Therefore, AODOP can serve as a solution to existing problems contributing to the development of a thriving blue future.

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