Wave Energy Converters: Barriers and Drivers

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Abstract

Wave energy has the most important renewable energy sources with many advantages compared to other types of renewable energies. The objective of this study is to provide an up-to-date investigation of the wave energy harvesting technology with emphasis on the main barriers and drivers of the wave energy converters development and utilization. The goal is to locate the best spot for wave energy converter (WEC) in the Red Sea region. The outcome of this study is to identify the most suitable converter system to harvest wave energy based on the most important criteria including wave depth, amplitude, wavelength, and frequency of the waves. These parameters along with environmental factors, sustainability development goals (SDG#14), and site constraints, have been assessed to develop a WEC device site-specific screening. Technical and social impacts were found to be deciding factors for the viability of wave energy exploitation.

Keywords
Wave Energy Converter, Wave Energy, Ocean Energy, Drivers, Barriers

1. Introduction

To shorten greenhouse gas discharge and to safe admissible for all countries, it is visible that renewable power sources will assume a key job. Universally, fossil fuel utilization is ~78.3% of the all-out part energy utilization, trailed by sustainable power sources with 19.2%. Customary biomass represents 8.9%, while the current sustainable power source has a level of 10.3%, controlled by sunlight and air. Internationally, the sustainable energy division between 2004 and 2013 (barring hydropower) expanded from 85 to ~560 GW. Representing the division was the wind industry with development from 48 to 318 GW, trailed by the photovoltaic segment from 2.6 to 139 GW (Rusu & Onea, 2018). Globally, the renewable energy sector between 2004 and 2013 (excluding hydropower) increased from 85 to ~560 GW. Leading the sector was the wind industry with growth from 48 to 318 GW, followed by the photovoltaic sector from 2.6 to 139 GW (Swenson, 2020). The growth in the renewable sector was due to several factors including political support, financial incentives, and reduction in the costs of technology making renewable energy cost-competitive. As the name implies, wave energy is the energy of the waves, collected and transformed into useful energy. It is considered as one of the promising renewable energy options with great potential in reducing CO_2 emission (CCR, 2018; Crus, 2008). However, wave power needs explicit ecological conditions to be made. The energy is similarly distributed between (i) the potential energy part, where the water is constrained against gravity from the wave trough and peaks, and (ii) the active vitality segment, that is, the water swaying speed. To utilize this power, it is imperative to draft a structure that can productively catch and collect the energy transmitted by the waves (Aderinto & Li, 2019, Ilyas et al., 2014). Another important factor is that the structure must have the option to endure the marine atmosphere; specifically, storm occasions wherein the wave power fundamentally increments. The present study attempts to locate the best spot for wave energy converter (WEC) in the Red Sea region by identifying the most suitable converter system to harvest wave energy. Besides, the study considers the social and environmental factors, as well as site constraints.

2. Literature Review

In a report by the World Energy Council (WEC, 2016), it has been reported that there is a potential of 32,000 TWh per year including 1300 TWh/year in the Mediterranean Sea and Atlantic Archipelagos (Cascajo et al., 2019). In 2019, the International Energy Agency (IEA, 2019) reported that marine development electricity generation increased by an estimated 16% in 2018. In the sustainable development scenario, 2000-2030, it is expected that ocean power generation reached 15 TWh (IEA, 2019). With the first WEC patent issued in 1799, the first WEC system was developed in France (Alamian et., 2014). Yoshio Masuda created the predecessor to modern wave energy systems in Japan in 1940 with the integration of the first floating oscillating water column into a navigation buoy (Masuda, 1986). Since then, more than 1000 patents have been issued; each project is described by different design and power take-off device (air, hydraulic, electrical, mechanical), describing the mechanism that absorbs and converts wave energy into electricity (Swenson, 2020). Wave energy converter research and development began in Great Britain in 1975 through several programs (MacCormick, 1981). Sweden constructed one of the world's largest commercial wave energy at Sotenäs, including 42 devices and producing a power of 1.05 MW. Another project was also installed in Ghjana including six devices with a capacity of 400 kW (WEC, 2016). The Norwegian government then adopted these policies. In 1985, on the coast near Bergen, Norway, significant efforts were made to build two real-size converters with a rated power of 350 kW and 500 kW (MacCormick, 1981). Activities in this field remained largely at the academic level in Europe until the early 1990s (Falcão, 2010). A small-scale, oscillating water column (OWC) built-in Islay, Scotland, in 1991, is the most notable achievement of this era (Falcão, 2015). Two OWCs were installed in Asia around the same time, including a 60-kW converter combined with a breakwater in the port of Sakata, Japan, and a 125-kW bottom-standing power plant in Trivandrum, India (Falcão, 2016). One of the failed devices of the time is the 2-MW converter in Scotland, destroyed by the waves. A 400-kW OWC was installed in Portugal in 1999, followed in Scotland in 2000 by a 300-kW Limpet ((Falcão, 2016; Polinder et al., 2005). The floating-point absorber SEAREV was first published in France in 2003 (Babari, 2009). Two years later, in Port Kembla, Australia, a new version of this absorber was developed and a semi-industrial 1:5 scale prototype, named Wave Dragon, was dropped into Denmark's water (Cascajo et al., 2019). Several converters were launched later in 2008, including a Pelamis in northern Portugal, 16 OWC systems in Mutriku, Spain, and an Oregon State University floating system. A floating system of 25 kW and an Osprey in the UK were also designed in Denmark (Alamian et., 2014). In 2010, the Ocean Linx was launched in Australia with eight air chambers and two engines, followed by PSFROG in the UK (Oceanlinx, 2019). Among other devices that have been deployed to date are salter energy converters (UK), point absorbers (Norway), tapered channels (Norway), energy-absorbing pedals (Japan), and Archimedes boys (Portugal) (Aderinto & Li, 2019; Cascajo et al., 2019; Alamian et., 2014).

3. Wave Energy Converters

Waves have the potential to provide a completely sustainable source of energy, which can be captured and converted into electricity by wave energy converter (WEC) machines (Aderinto & Li, 2019; Cascajo et al., 2019). These WECs were designed to extract energy from the shoreline to the deeper offshore waters. There are currently about 80 wave energy conversion technologies available. The type of WEC chosen will depend on the physical characteristics of the specific location, the types of local waves, and their working principles. WECs can be divided into four groups.

3.1 Attenuator

An attenuator is a floating device that runs parallel to the path of the wave and rides the waves effectively. These instruments extract energy from the two arms relative motion as they move through the wave. Floating devices of this type include the Pelamis (Alamian et., 2014, 2014), Wave Star (Masuda, 1986), Salter Duck (McCormick, 1981), and Anaconda (Falcão, 2010) are shown in Table 1.

Table 1. Characteristics of attenuator wave energy conversion systems

Wave absorber	Type, water depth (m)	Mean wave power (kW/m)	Output power (kW)	Generator position
Pelamis	Floating ocean surface 50-60	15-40	750-1000	Within the body
Wave Star	Floating in the ocean 2-30	24	500-6000	Overwater surface
Salter Duck	Floating in the ocean 2-30	24	375	In water
Anaconda	Floating in the ocean 20	50	1000	Out of water

3.2 Point Absorber

A point absorber is a floating object that absorbs energy from all directions by traveling to/near the surface of the water. Depending on the displacer/reactor configuration, the power take-off system can take several forms. Examples of this type of WEC are the SEAREV Anaconda (Falcão, 2015), L10 Anaconda (Falcão, 2016), OPT power (Babarit, 2009), AquaBoy (Cascajo et al., 2019), Archimedes Buoy (AREAN, 2019), Uppsala (Bahaj, 2011), WaveBob [13], WaveRoller (Alamian et al., 2014), BioWave (Kassem, 2015), and Pendulum (OPT, 2008) are shown in Table 2.

Table 2. Characteristics of point absorber wave energy conversion systems

Wave absorber	Type, water depth (m)	Mean wave power (kW/m)	Output power (kW)	Generator position
SEAREV	Floating ocean surface 50	40	500	On the ocean surface – inside the body
L10	Floating in the ocean	20	10	In water – inside the body
OPT power	Fixed in the ocean 30-60	50	40-500	In water – inside the body
AquaBuoy	Fixed ocean surface 40-80	15-50	250	On the ocean surface – inside the body
Archimedes Buoy	Fixed seabed 30-60	15	250	In water
Uppsala	Fixed seabed	20	5	In water
WaveBob	Fixed ocean surface over 50	20-70	500	In water
WaveRoller	Floating seabed 6-23	15	300	shore
BioWave	Fixed seabed 6-23	50	250-1000	In water
Pendulum	Fixed shore	15	20-300	Out of water

3.3 Oscillating Water Column

An oscillating column of water is a hollow structure that is partially submerged. It is exposed to the sea below the waterline, supporting an air column on top of a water column. Waves cause the column of water to rise and fall, compressing and decompressing the column of air in turn. The trapped air will flow through a turbine into and out of the atmosphere, which typically can rotate regardless of airflow direction. The rotation of the turbine is used to generate electricity. Floating and fixed examples of this type are OceanLinx (Weinstein et al., 2004), Limpet (Polinder et al., 2005), Pico Plant (Joubert et al., 2009), Osprey (Breslin, 2005), and Mighty Whale (López et al., 2013) are shown in Table 3.

Table 3. Characteristics of oscillating water column wave energy conversion systems

Wave absorber	Type, water depth (m)	Mean wave power (kW/m)	Output power (kW)	Generator position
OceanLinx	Floater off-shore 5-50	50	200-1500	Above free-surface
Limpet	Fixed on-shore 15	15	500	On-shore
Pico Plant	Fixed in the ocean 7	40	400	Above free-surface
Osprey	Fixed in the ocean 15-20	50	500	Above free-surface
Mighty Whale	Fixed ocean surface 40	15	110	Above free-surface

3.4 Overtopping Device

Overtopping devices capture water as waves break into a storage reservoir. The water is then returned to the sea, passing through a conventional low-head turbine which generates power. An overtopping device may use 'collectors' to concentrate the wave energy. Floating and fixed devices of this type are the Tapchan (bioWAVE , 2020), Wave Dragon (Kofoed, 2006), and SSG (Vicinanza, 2012).

Table 4. Characteristics of overtopping wave energy conversion systems

Wave absorber	Type, water depth (m)	Mean wave power (kW/m)	Output power (kW)	Generator position
Tapchan	Fixed shore 20	40	350	Out of water
Wave Dragon	Floating ocean surface 20-30	24	40	In water
SSG	Fixed shore 15	19	150	Out of water

4. Barriers and Drivers

4.1 Identification of Site

To choose a suitable location for WEC, it depends on many factors. In our research focusing on the Red Sea with emphasizing to NEOM city. The monthly distribution of mean wave height is shown in Figure 1. Gulf of Aqaba is to be considered, since the mean wave height has been found to be 1.5m, and it is near shore. Also, according to the monthly distribution of mean wind speed, winds are stronger over the Gulf of Aqaba as shown in Figure 2. A total of 8 points were selected to test the potential of wave energy at the Neom coastline. The distribution of study points is presented in Figure 3 (denoted from P1 to P8).

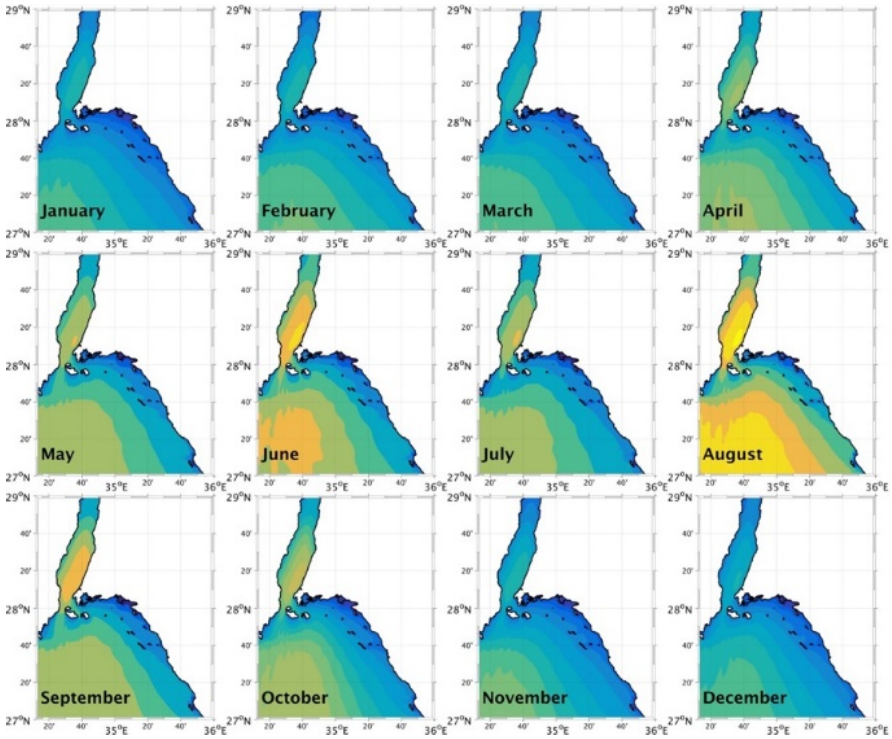

Figure 1. Monthly distribution of mean wave height from one year of shallow water wave simulation (2001)

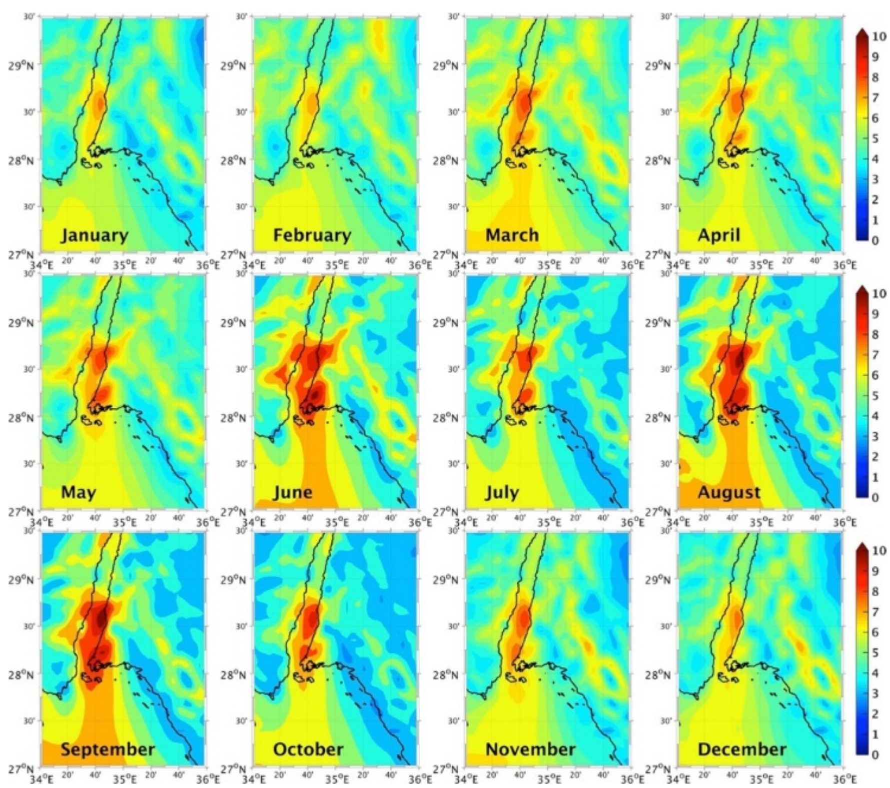

Figure 2. Monthly distribution of mean wind speed from the 15 years of WRF simulations (2001-2015).

Figure 3. Selected Study Points

4.2 WEC Selection

Based on Table 5**,** the minimum mean wave power necessary to activate a WEC is 2.8–3.4 kW/m. "Fixed- and floating-point absorber devices," indicate that Point absorber devices might present power output of 4 kW.

Table 5. Summary of operating depths, mean power ranges and output power ranges for wave energy converter (WEC) devices

WEC Concept	Type	Depth Range (m)	Mean Wave Power Range (kW/m)	Output Power Range (kW)
Wave activated body	Floating	2-75	10-70	68-2250
	Fixed	1-40	10-50	5-100
Point absorber	Floating	10-2500	3.4-80	4-500
	Fixed	10-43	2.8-40	221-600
Oscillating water column	Floating	5-50	4-50	153-1500
	Fixed	4-14.5	20-60	31.7-2000
overtopping	Floating	20-40	60	625-940
	Fixed	6-20	14-30	49-350

4.3 Social Challenges and Environmental Challenges

The Sustainable Development Goals (SDGs), also known as the Global Goals, were adopted by all United Nations Member States in 2015 as a universal call to action to end poverty, protect the planet and ensure that all people enjoy peace and prosperity by 2030. The 17 SDGs are integrated—that is, they recognize that action in one area will affect outcomes in others and that development must balance social, economic and environmental sustainability. Implementing the ocean wave energy to produce electricity will achieve SDG #7: Affordable and Clean Energy, Ensure access to affordable, reliable, sustainable and modern energy for all. On the other hand, for wave energy converter installation, it is important to take into SDG#14 that states "Conserve and sustainably use the oceans, seas and marine resources for sustainable development". The main goal here is to sustainably manage and protect marine and coastal ecosystems while enhancing the conservation and the sustainable use of ocean-based resources.
Due to the high abundance of birds, fish, tortoises, and corals and the already endangered biodiversity. WEC project deployment could cause cumulative impacts and jeopardize marine and coastal ecosystem health and resilience. As

coastal communities are highly dependent on the goods and services provided by these ecosystems, such as fishing and beach safety, any changes to these habitats could have serious social implications. On the other hand, setting up WECs could produce environmental benefits, such as setting up fishing exclusion zones where endangered fish populations could recover. Here SDG #14: Life Below Water, Conserve and sustainably use the oceans, seas, and marine resources for sustainable development will be achieved. At the coasts of NEOM, we have to take the coral reef at the shoreline into account. Coral reefs in the Red Sea north are a regional focal point for their exceptional resistance to climate change. Given the importance of the Red Sea coral reefs and other distinct marine structures and ecosystems in Saudi Arabia, As a member of the World Heritage Convention since 1978, the Ministry of Culture has been collaborating with UNESCO to recognize coral reefs in the Red Sea and other unique sites in the Red Sea as UNESCO protected sites and classified as World Heritage Sites, with the goal of protecting them as important natural assets for future generations (Saudi, 2019). Also, another consideration to take into account is the location of Sharma Palace along the coast located in the southwest of the NEOM region.

4.5 Operation and Maintenance Challenges

The operation and maintenance stages of wave energy converter projects refer to their performance and survivability. Preventive maintenance is required to avoid corrective maintenance of the devices.

4.6 Performance Improvement

- One of the most challenging issues in wave energy harvesting is the transformation of the irregular waves into a smooth electrical output, acceptable to the electrical grid, requiring some type of energy storage system or a reactive compensation means. The WECs need not only to adapt to changes in wave height and period, but they also need to be able to align themselves on the wavefronts. The WECs are composed of a number of components: (1) the structure and the primary mover collecting the wave energy, (2) the base or mooring that holds the structure and the primary mover in place, (3) the power take-off (PTO) system that transforms mechanical energy into electrical energy, and (4) the control systems that safeguard and maximize operating efficiency (Felix et al., 2019).

- **Cost Reduction**

Cost reduction is perhaps the most critical element for improvement, to ensure that ocean energy becomes competitive. Stated that expected improvements in the next generation of wave technology could reduce the costs of power take-off by 22%, of installation by 18%, and operation and maintenance by 17%, while costs in foundations and mooring, and grid connection could fall by 6% and 5%, respectively (Rusu et al., 2018). Another promising option to cut costs is by WECs sharing the infrastructure of existing offshore wind parks.

5. Results & Discussion

5.1 Selection of suitable WEC

Fixed- and floating-point absorber devices and floating oscillating water column devices operate with 2.8–3.4 kW/m and 4 kW/m, respectively, as shown in Table 5. Indicates that Point absorber devices might present power output of 4 kW, whereas the floating oscillating water column devices might yield 153 kW. Regarding the mean wave power at the study points, as shown in Figure 4, P2 presents the heights mean wave power 1.98 kW/m.

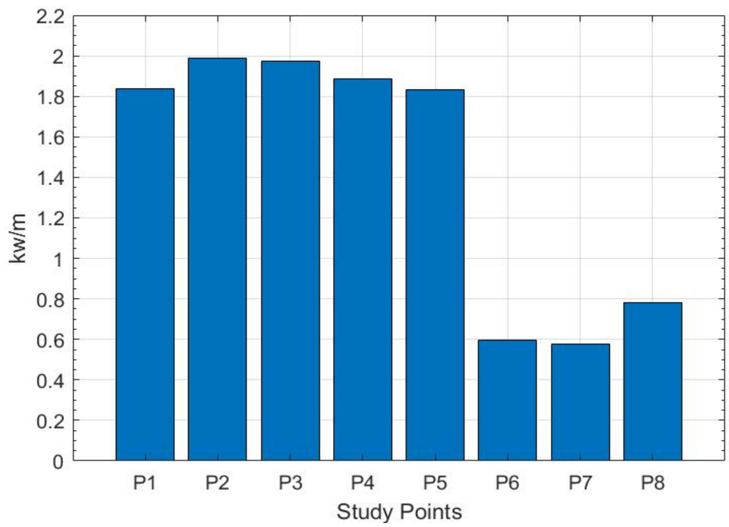

Figure 4. Annual mean wave power calculation for 12 years (2006 – 2018)

Build a new infrastructure that combines a breakwater and a wave energy converter (Mustapha et al., 2017; Arricife, 2020). It called Overtopping Breakwater for wave Energy Conversion (OBREC) Figure 5. Overtopping Devices (OTDs) has a reservoir that is filled with water from waves running up a slope located at a higher level than the surrounding sea. The energy of water flowing back to the sea is used to power a hydraulic turbine as shown in Figure 5. With the installation of the OBREC device along 500 m of the breakwater in Madagascar, considering a breakwater of 500 m, estimated a total power of 115.5 kW, corresponding up to about 1010 MWh/year, Table 6.

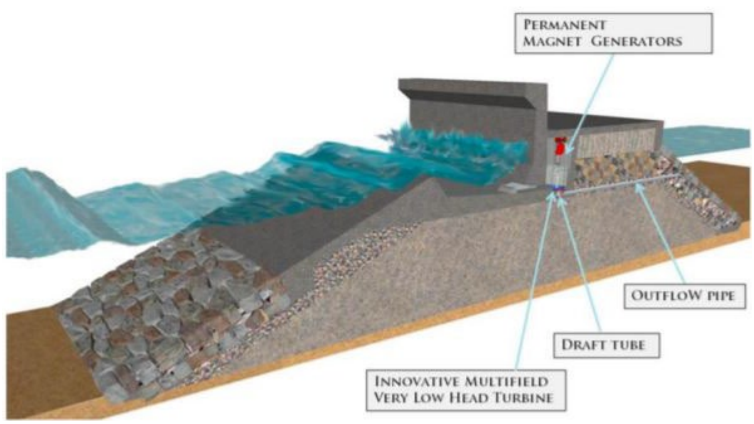

Figure5. OBREC working principle (Arrecife, 2020)

Table 6. Comparison of some WEC technologies

Wave Energy Converter	Operating Principle	Water Depth (m)	Mean Wave Power (kW/m)
SSG	OTD	6-18	14-16
OBREC	OTD	25	2-8
Wave Star	Floating bodies	10-20	2.8-5.2
LIMPET	OWC	6	20
Pico	OWC	8	37.9

ARRECIFE Energy Systems (Arrecife, 2020) Figure 6, a new wave energy converter designed to operate at low wave heights between 1 and 5 m, while other WECs needed 5 to 8 m waves for activity, Figure 6. The ARRECIFE specification considered the first operating system that directs turbines, opposes the wave which absorbs more energy; it obtains energy from waves, currents, and tidal flows, installed offshore, away from the coast and at great depths, low O&M cost, Transportable system and fixable onshore.

Figure 6. ARRECIFE Energy Systems (Arrecife, 2020)

6. Conclusion

In this study, wind and wave energy in the Red Sea region has been investigated using a data series that has been developed via numerical modeling over 12 years. The goal was to select the most suitable area for the installation of WECs. The wave power has been analyzed using the data from 8 study points by incorporating wind and wave data between 1985 and 2015. The highest peak period selected in the present study is based on the wave hindcast generated on a 1-km resolution grid. The wave power per unit of crest length (kW/m), the significant wave height, is calculated in the selected areas. Based on the preliminary results, the Gulf of Aqaba with a mean wave height of 1.5 m, is a good candidate for a WEC. Technical and social impacts were found to be deciding factors for the viability of wave energy exploitation. At NEOM coastline, we must take into consideration the coral reef at the shoreline. Coral reefs in the north of the Red Sea are a global focus for their remarkable resilience to climate change. Based on this preliminary study, a fixed-point absorber could be installed at P2 and P3; however, it will provide a power output during September. A hybrid system wind-wave might be another solution, however, to install wind turbines it should be on a fixed surface/substructure, which is not going to work with the selected WEC above. Other solutions are being investigated and more work in underway to complete this part of the thesis and include an economic study.

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Biographies

Misaa Alkhayyat is a master student in Renewable Energy Engineering at Effat University, Jeddah, Saudi Arabia. She earned B.S. in Mechatronic Engineering from California State University, Chico, USA. She Nominated as one of the Top 10 Business Plans presented at the1st Annual Entrepreneurship Contest "Tamakon" at the Saudi Arabian Cultural Mission SACM, 2014. Earned U.S Patent 8804327 B2 Portable Workstation. filed October 1, 2012 and issued August 12, 2014. She Awarded Bronze Medal at the 4th International Invention Fair in the Middle East hosted by the Kuwait Science Club, 2011. Misaa Alkhayyat Awarded the First place in the Inventions and Patents at the 3rd Scientific Conference for students at KAU, 2011.

Dr. Tayeb Brahimi, Assistant Professor at the Department of Electrical and Computer Engineering (ECE), at Effat University, Jeddah, KSA, received his Ph.D. (1992) and Master Degree (1987) from University of Montreal, Canada. He has worked as Research Scientist under Bombardier Chair/Canadair from 1992-1998. In 1998, he joined Jeppesen DataPlan in California, then Peregrine System as a Technical Support Analyst, Quality Assurance Engineer, and Consultant for Electronic data interchange (EDI) in Dallas, Texas. Dr. Tayeb Brahimi has been a consultant at IONPARA Inc. for wind energy and aeronautics. He published more than 80 articles in scientific journals, international conferences, on novel methodologies of teaching and learning, renewable energy, sustainability, and machine learning. Among other activities, he is a reviewer for many international journals, invited speaker by the Japan Society of Mechanical Engineering, the Gulf Educational Conference as well as the Int. Conference on Eng. Education & Research. He also participated in Public Debate on Energy organized by the Government of Quebec, Canada. Current research interest relates to renewable energy (solar, wind, wave, and waste to energy), sustainability, machine learning, use of technology to support learning, engineering education, MOOCs, and Makerspace. Other areas of interest include integrating innovative Islamic heritage into the STEM.

Dr. Ibrahim Hoteit, an associate professor in the Earth Sciences and Engineering program and the Applied Mathematics and Computational Sciences program at KAUST. He is currently the associate director of the Saudi

Aramco-KAUST Center for Marine Environmental Observations (SAKMEO) and the PI of the Virtual Red Sea Initiative, a joint project with with MIT/SIO/PML. Prior to joining KAUST in 2009, he worked as a research scientist at Scripps Institution of Oceanography of the University of California, San Diego. Dr. Hoteit's research interests are in modeling and simulation of ocean and atmospheric systems on supercomputers, with specific interest in data assimilation and inverse problems and associated uncertainty quantification. Dr. Hoteit co-authored more than 150 scientific papers and is a co-recipient of five best conference paper awards. He is a member of the American and European Geophysical Unions, the Society of Industrial and Applied Mathematics, and an elected member of the UNESCO Center of Pure and Applied Mathematics. Dr. Hoteit earned his M.S. (1998) and Ph.D. (2002) in applied mathematics from the University of Joseph Fourier, France.

Dr. Sabique Langodan, Dr. Langodan's research focuses on modeling and understanding ocean processes in the Red Sea, especially those related to ocean waves. He is currently investigating the variability and trends of wind and waves in the Red Sea, and their relationship to the climate processes. Ph.D., Earth Science and Engineering, King Abdullah University of Science and Technology (KAUST), Thuwal, KSA, 2016. He earned his M.S., Ocean Technology, Cochin University of Science and Technology (CUSAT), India, 2010. And M.S., Physics, Aligarh Muslim University (AMU), India, 2008. His B.S. in Physics from University of Calicut, India, 2006.