Wave Energy Harnessing for Marine Propulsion-An Approach Towards Energy Efficient Shipping

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Abstract

The quest for clean sources of energy is still too far from the challenge faced by the modern world of the 21st century. An increasing amount of industrialisation is continuously resulting in a gradual depletion of fossil fuel and extensive damage to the environment. The shipping sector, one of the biggest and ever-expanding industries of the world, almost exclusively uses fossil fuels to meet its energy needs. Due to the nature of this industry, there is always availability of waves at sea which can be harnessed and utilised as a source of energy though it hasn't been utilised yet in vast canvas. Wave energy can be considered as a robust form of energy and an effective alternative to fossil fuel if it can be properly harnessed. This study focused on how energy could be produced from ocean waves and could be used efficiently in the propulsion system. Methodology revealed here is basically to show the viability of the application of Wave Energy Converter (WEC) technologies in a vessel while at anchorage and port, since the application of WEC during sailing of a vessel hasn't still been proved as an efficient option because of vessel size associated with additional drag resistance. Aim of this paper is to elucidate mathematically if the harnessing is possible at anchorage time and additionally describes the theoretical prospect of mass implementation possibility at the port to affirm energy-efficient shipping. The outcome of this research could lead to an energy-efficient and economical propulsion system with the utilisation of a renewable energy source as well as a reduction in carbon dioxide emissions.

Keywords: Emission Reduction, Energy Efficient Shipping, Renewable Energy, Wave Energy Conversion

Introduction

The shipping industry is the backbone of the global economy. Approximately 90% of the tonnage of all traded goods is transported by ships as estimated by the International Chamber

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of Shipping. The total marine fleet of the shipping world altogether consumes between 250 to 325 million tons of fuel annually [The International Maritime Organization(IMO) estimates that between 2007 and 2012] and it is blamed for approximately 2.8% of annual global greenhouse gas emissions. More stringent regulations and measures are enforced by MARPOL (The International Convention for the Prevention of Pollution from Ships) to throttle down carbon dioxide emissions 20% by 2020, 50% by 2050. In addition, rising of bunker fuel prices in a global volatile market and low freight rates opt-out another reason for the shipping company to find the best alternative way to reduce dependency on fuel. As more than 70% of the earth's surface is covered by ocean, it is theoretically estimated that the ocean holds energy resources about four times the global electricity demand (Nielsen, 2012). In this context, the energy-efficient shipping idea incorporated with renewable energy comes to focus.

Solar, wind and wave are the basic forms of renewable energy. Among these, the wave has the high-density energy form. As a renewable source of energy, wave energy has significant advantages over other renewable sources of energies (Clément et al. 2002). While solar energy intensity is typically 0.1–0.3 kW/m² in a horizontal surface, converted to an average power flow intensity of 2-3 kW/m², wave energy in the vertical plane is perpendicular to wave propagation (Falnes 2007). Wave power devices can generate power up to 90% of the time compared to 20~30% for wind and solar power devices (Polinder and Scuotto 2005). Most importantly, it has limited negative environmental impact in use. Table 1 indicates a comparative analysis of effective power obtained from renewable sources of energies.

Table 1. Comparison of effective power obtained from renewable sources (Nat, Sommer, 2013)

Source	Available energy in Northern scenario (North sea)	Available energy in Southern scenario (Mediterranean)	The energy at best condition
Sun	23 kW	45 kW	55 kW
Wind	48 kW	37 kW	67 kW
Waves	106 kW	18 kW	319 kW
Total	113 kW	26 kW	331 kW

As seawater is about 850 times heavier than air, it contains a lot of energy while in motion. However, power per length of a wave crest, [W/m], is a fair measure of the energy contained in waves where in comparison to the energy flux of wind and solar energy are presented in the unit of [W/m²].For this study, a worldwide shipping route, composed of 496 points using great circle navigation is considered for calculating average energy flux for a given amount of time. (Af, Klinteberg,2009). From below table-2, the estimated result is pretty evident that the average energy flux of wave along this route varies between 10 kW/m and 50 kW/m with a yearly average of 26 kW/m.

Table 2: Average monthly energy flux along the worldwide route during January-December 2007 (Af, Klinteberg, 2009)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg. in Year
Wave energy flux (kW/m)	49	49	34	28	15	12	12	11	15	21	29	41	26

With an estimated average energy flux of J = 26 kW/m, a ship following the worldwide route will be exposed to an energy of roughly 4 MW on average. This vast pull of energy can save large amounts of fuel if properly exploited and utilised in the propulsion system.

To conduct the methodology,

- Few data are required.
  - Data of the vessel in anchorage and port
  - The data of wave period and height at that certain location
  - Data of WEC to be applied in the vessel
- Primary data is collected from MarEng Shafiul Bari, working as a Fourth Engineer in MV Great Royal by an interview.
- Secondary data were obtained from books, journals, the Internet, and other relevant articles.
- The equation to calculate the power generated by WEC technology supplied to vessel is studied from a book 'Marine Renewable Energy Handbook' edited by Bernard, Multon.

To validate the study,

- It is needed to calculate how much average wave power is available in Kutubdia all over the year
- How much power can be captured in WEC
- How much power can be contributed to the ship's power main

So, accumulating all the data, this study will show how to gain a positive output mathematically to ascertain the viability of implementing WEC technology in the vessels.

Wave Formation and Wave Anatomy

Wave energy is basically another concentrated form of solar energy, which is produced by wind flow over the surface of the ocean. When the sunray strikes the atmosphere, it becomes hotter. As a result of the temperature differences created in the atmosphere, the air moves from hotter regions to cooler regions, thus making wind energy to flow. Waves can also be created from landslides, gravitational attraction, and other earth movements i.e. tectonic movement.

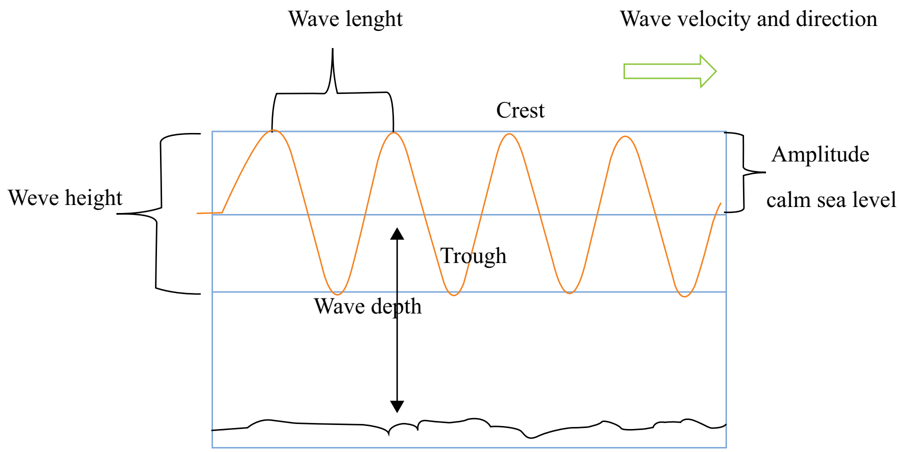

Figure 1: Wave anatomy

Wave Energy Conversion Device and Technology

There are many technologies being invented to capture energy from ocean waves. These technologies include converting wave to electricity and converting wave to useful propulsive thrust. Among those, some technologies can be feasible to be implemented in vessels.

Different types of WEC are available in the world. Basically, they can be categorised into three types:

a) Wave activating body- extracts power from up and down motion of the waves, which depends upon the design and building characteristics. Different types of Wave Activating Body are there.

- Attenuator (Pelamis)
- Point absorber
- Bulge wave converter
- Oscillating wave surge converter

b) Oscillating water column- extracts power from the vertical oscillating motion of wave and converts to air pressure.

c) Wave capturing overtopping device - extracts power from the flow of water-assisted by wave and gravity

Besides, there are some other technologies available like Hydrofoil/ thrust generating foil technology and WITT (Whatever Input to Torsion Transfer) technology. Basically, these technologies can be implemented in vessels in three ways: during sailing, at port and port operation and at anchorage.

Wave Energy and Wave Power Formula

The power of a wave is determined by the "Wave Power Equation". Wave power is defined by the flow of energy through a vertical surface perpendicular to the direction of its propagation. It could, therefore, be expressed in Wm^{-2}. However, this is not the usual usage, and it is preferable to quantify wave power in Wm^{-1} (watts per metre of wave front).

To calculate the flow of energy, it is necessary to find out the mechanical energy of a vertical column of water and then multiply with the speed of the wave. The mechanical energy of a water column is the sum of its potential and kinetic energy. For loss-free propagation of the wave, both of them are equally written as follows in the case of a wave with sinusoidal formation:

$$< Ek\ (t) > = < Ep\ (t) > = Em/2 = (\rho wgH\string^2)/16$$

Where,

ρ_w = Density of seawater (1,025 kg/m³)

E_k = Kinetic energy of water column

E_p = potential energy of water column

g = gravity

H = wave height

$E_{m=}$ mechanical energy of water column

When the depth of the water is infinite, the group speed, v_g (i.e. speed of energy propagation) is written:

$$Vg(T) = gT/4\pi$$

Where T is the period of the sinusoidal wave.

So, the power per metre of the wave front of a sinusoidal wave is therefore equal to:

$$Pw = E_m v_g = H^2T \approx 980\ H^2T\ (W.\ m^{-1})$$

It is the simple equation of ideal wave power avoiding complexity. This equation is valid for unidirectional and uniform sinusoidal waves.

Hydrodynamic Performance of Wave Energy Converters

How much power can be captured by WEC technology from available wave power can be calculated from the hydrodynamic efficiency of WEC technology. In case of capturing energy from waves to a WEC technology, the ratio of power absorbed by WEC to the wave energy flux (wave power per meter length of wavefront) is defined as capture ratio, B_w.

$$\text{So, } B_w = Pabs/Pw$$

This relation is homogeneous to a given length. It may be interpreted as the wave-front width of wave energy absorbed by the system. From the definition, it is found that hydrodynamic performance is the ratio of capture width to relevant dimension,

$$\eta = B_w / B$$

$$\text{or, } \eta = Pabs / (Pw \times B)$$

So, power absorbed by a WEC can be written as follows:

$$Pabs = Pw \times B \times \eta$$

Where,

Pabs = Wave power absorbed by the WEC

Pw = Wave power per meter length wave front

η = Hydrodynamic performance of wave energy converters

B = Size or dimension of WEC device (can be length or width, depends on which principle the wave energy converter works. Such as for Pelamis, it is the length.)

If power take-off efficiency is €, then electricity supplied to ship from WEC device is,

$$Ptotal = Pabs \times €$$

Findings and Result

In this section, it can be calculated mathematically to find out how much power can finally be contributed to the ship's power main. For this process, a vessel named MV Great Royal is considered here for a period of 26 June 2018 to 13 July 2018 at Kutubdia anchorage, Bangladesh. Since the purpose of this research is to study the viability of WEC technology while the vessel is standstill, the duration of the vessel at anchorage is only to be considered. For better understanding, all the specifications of the vessel are provided below:

Table 3: Particulars of the vessel considered for the study (Interviewed by the authors)

Ships' name and details	Location of anchorage	Time at anchorage In Kutubdia	Average generator load	Average fuel consumption
MV. Great Royal Gross Tonnage: 23,263 MT Deadweight: 42,174 MT Length Overall x Breadth Extreme: 180m × 31m	Kutubdia	26 June 2018 to 13 July 2018	360 kW	2.8 Tons/day

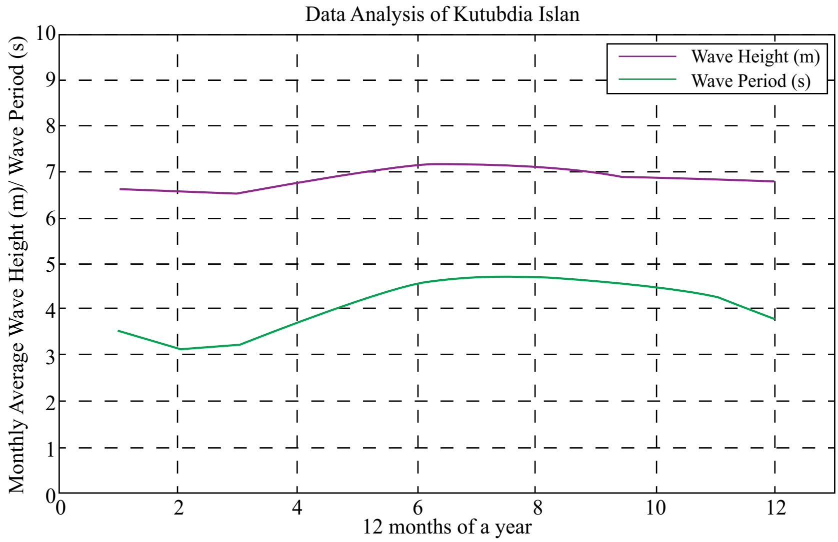

Figure 2: Wave height and period at Kutubdia round the year (Samrat, Rahaman, Mamun,Adib, Badhan,Ahmed, 2014)

From Figure 2, it can be obtained that from June to July in Kutubdia, average wave height and wave period is 7.2 m and 4.7 s. So, theoretically how much wave power is available at that time at sea, can be gained roughly by the following formula:

$$Pw = Emvg = \rho wg2/32\pi \text{ H2T} \approx 980 \text{ H2T (W. m-1)}$$

So, wave power per metre length of the wavefront is, $980\times (7.2)^2\times 4.7 \text{ W.m}^{-1}$

$$= 238775.04 \text{ W.m}^{-1}$$

$$= 238.77 \text{ kW.m}^{-1}$$

Here, a small size WEC is considered for easy handling and carrying out of operation. Large or medium size WEC can be applied in a vessel for more power, but ship personnel may face difficulties while installing on seawater surface.

From the equation of power absorbed by WEC, power absorbed by a small heaving buoy (size of 5 m) such as a small point absorber can be easily found out in such condition with the values of B and η obtained from table 4.

$$P_{abs} = P_w \times \text{B}\times \eta$$

$$= 238.77\times 5\times 0.09 \text{ kW}$$

$$= 107.44 \text{ kW}$$

If this power is converted to electricity with minimum power take-off efficiency € = 30%, the amount of power supplied to ship is,

$$\text{P} = (107.44\times 0.3) \text{ kW}$$

$$= 32.23 \text{ kW}$$

If 5 number of small size point absorber heaving small buoy can be used while ship anchoring, total power supplied to the ships' power main is,

$$P_{total} = (32.23\times5)$$
$$= 161.15 \text{ kW or } 161 \text{ Kw}$$

So, generator load can be reduced by 161 kW, from 360 kW to 199 kW saving fuel about (2.8/360) × 161 tons

= 1.25 tons roughly.

Table 4: A list of hydrodynamic performance of different types of WEC. (Multon Bernard, 2012:348)

Category	Sub-category	Average hydrodynamic performance	Min.	Max.	Typical Size	Reference dimension
Oscillating water column		33%	20%	45%	30m	Width
Overtopping system		13%	4%	23%	300m	Width
System driven by the waves	Small heaving buoy	9%	3%	14%	5m	Width
	Large heaving buoy	29%	19%	42%	20m	Width
	Bottom fixed oscillating flaps system	41%	25%	65%	20m	Width
	Floating oscillating flaps system	20%	14%	36%	25m	Width
	Floating system combining surge/ heave/ pitch	17%	6%	27%	30m	Width
	Heave/ yaw	6%	5%	7%	150m	Length

For port, multiple arrays of WEC technology can be implemented in deep seaport or seaport. But this won't be effective if the water depth is less than 30-40 metres, as large size WEC technology unable to work efficiently in shallow water. As Bangladesh has gradual slopping down of continental shelf to the seabed, it is not possible to find enough depth in Kutubdia or Chattogram port or even Payra port for implementing WEC technology. But apart from Bangladesh, it is possible to find enough depth for successfully implementing WEC technology in other geographical port locations all over the world. In such kind of geographic locations, commercial installation of robust size WEC technology, for example, Wave Dragon, Oyster, Pelamis can contribute to a huge amount of electricity in port, which can be used for cold ironing (supplying shore power to ship). From table 5, we can notice that a large size wave dragon can have a power rating of 7000 kW/ single unit. So, theoretically, 2 units of wave dragon can supply (2 × 7000) = 14,000 kW = 1.4 MW, which can annually supply about 12264 MW of electricity to shore.

Table 5: Capacity of different types of WEC (Wave Energy Converters)(Rusu, Egen, 2013)

Device	Power per Unit (kW)	Movement	Depth (m)	Size
Oceantec	500	heave	30–50	medium
Pelamis	750	surge & heave	50–70	medium
P P Converter	3620	heave	deep	large
Wave Dragon	7000	Overtopping	30–50	large
Seabased	15	heave	30–50	small
Aqua Buoy	250	heave	>50	small
AWS (Archimedes Wave Swing)	2320	heave	40-100	Medium
Langlee	1665	Oscillating flaps	deep	Medium
OE Buoy	2800	Oscillating column	Deep	Medium
Wavebob	1000	Heave	deep	Medium

Discussion

The power saved per day over anytime of the year:

It is calculated by the equation described above in methodology. This discussion is valid for any ship staying at Kutubdia anchorage with 5 number of small size point absorbers heaving small buoy.

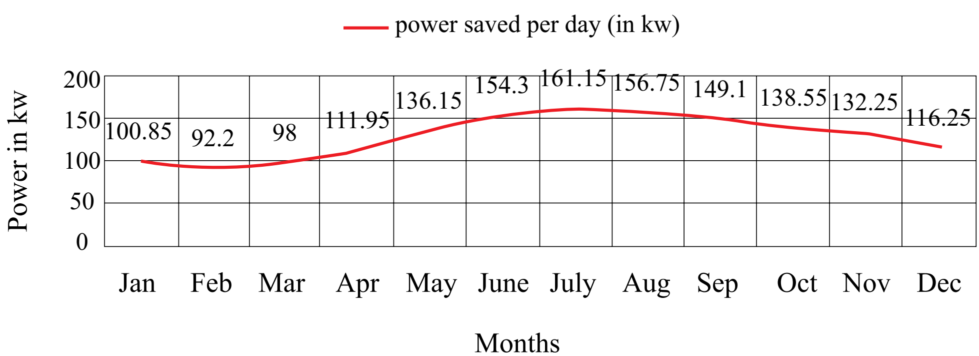

Figure 3: Power saved per day throughout the year

Reduction of CO_2 emission

It is estimated that specific CO_2 emission of HFO (Heavy Fuel Oil) is 3.11 kg CO_2/kg fuel.

So, CO_2 reduced = fuel saved × specific CO_2 emission

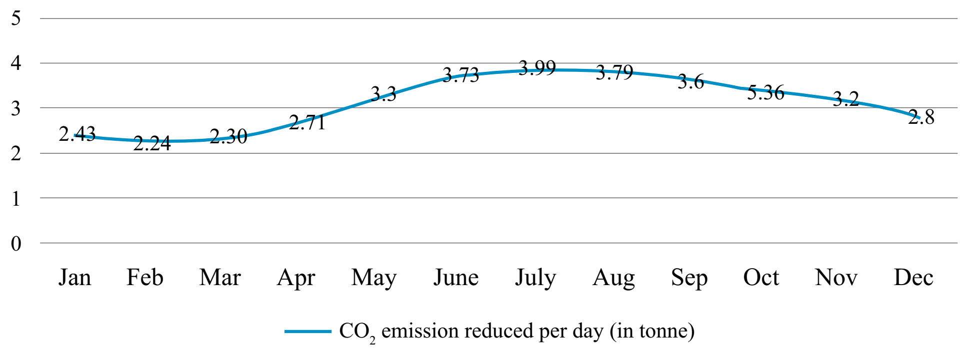

Figure 4: CO_2 emission reduced per day throughout the year.

Cost Analysis

Fuel saved

Amount of fuel saved is calculated by taking into account the average fuel consumption per kilowatt power production of that vessel mentioned, i.e.

Fuel saved = power saved per day× (2.8/360)

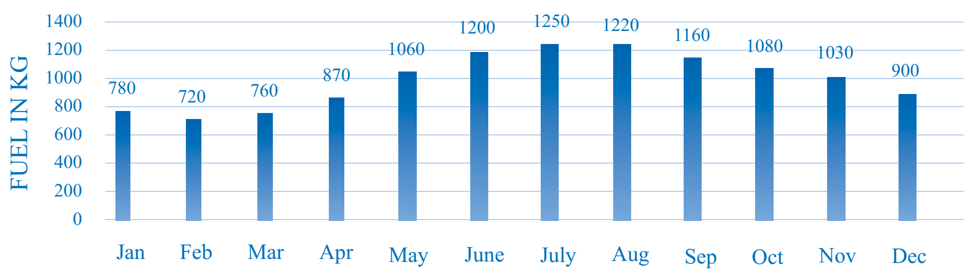

Figure 5: Fuel saved per day around the year in KG.

Cost saved

According to the world market, global bunker price is 489 USD per MT (Metric Ton)

So, Cost saved = (fuel saved × price).

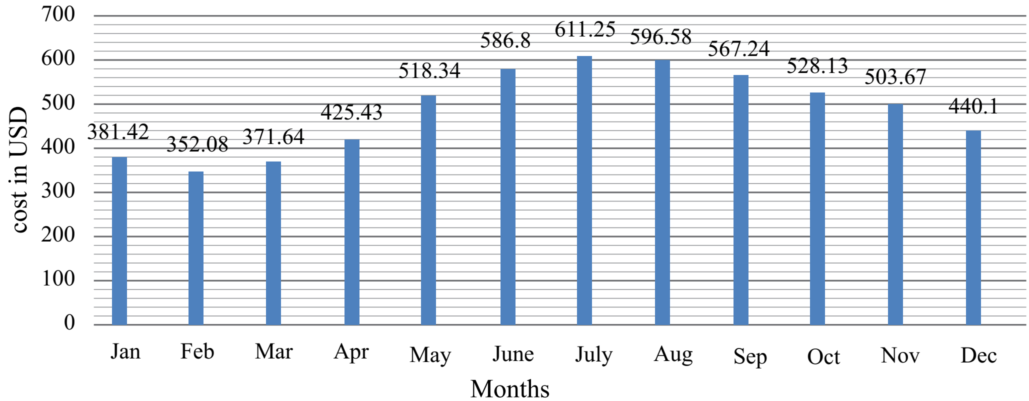

Figure 6: Cost saved per day around the year

Here, the smallest WEC is considered with the least efficiency of power uptake, so power production is less. If to consider medium or large WEC, then power production would be more undoubtedly. Other WEC technologies such as Anaconda Bulge wave converter technology seemed promising, could be proved viable in a ship, but lack of data and unconfirmed information didn't assist to carry out the calculation.

The small heaving point absorber type WEC is considered regardless of the depth of installation in the sea. It is demanded by the manufacturer that a single unit point absorber, Aqua Buoy of 6m diameter with 50 m depth can generate 250 kW depending on sea state. In that case, instead of installing 5 units, only a single unit Aqua Buoy type WEC can contribute enough to reduce fuel consumption of that vessel.

As some geographic location, such as Bangladesh doesn't have enough depth in the seabed, so apart from WEC technology, other tidal energy conversion technology can be proposed. High torrent characteristics of Karnaphuli River in Bangladesh may also permit this. But as tidal energy is beyond this study domain, this concept is not focused here. Other ports and deep seaports area over the world having enough depth could be proved as a worthy example of the energy-efficient port to ensure an energy-efficient propulsion system in shipping all over the world.

The cost of implementing WEC technologies may be expensive in the short term but can give a long-term cost-efficient return for the shipping company as well as significantly contribute to the emission reduction and a better shipping environment.

Conclusion

Though a propulsion system completely based on wave energy is yet to be implemented, wave energy has a lot more to contribute to the shipping sector. While fossil fuel is nearly running out, at the same time adverse effect on global climate urges for energy efficiency in the shipping industry. To ensure this, wave energy has been proved a better option of having more advantages than other green energy sources such as wind and solar, due to its higher energy density and easy availability. In the context of exploiting and utilising wave energy in seagoing vessels while sailing, frictional drag effect and wave resistance of WEC devices, slow speed functioning of devices, a slower speed of the vessel and less effectiveness of these technologies in larger ships etc. result in drawbacks and not fulfilling requirements. Only WITT WEC seems promising. Hence, authors went for evaluating the concept of feasibilities of wave energy technologies to near shore, port, harbour, deep seawater ports and vessels while anchoring, which theoretically seems satisfying their aims by significantly reducing fuel consumptions and CO_2 emissions and saving cost. These benefits may vary due to different place, condition and state of the sea.

Though all of these wave technologies are not commercially viable yet, testing of their prototypes proved good working. This study can pave a long and effective way in better and cost-efficient designing of these technologies, which could make it possible to easily and economically fit in vessels in vast prospect. In the near future, this research will surely enlighten higher efficient power benefits making a great step in the way of ensuring viable and energy-efficient shipping all over the world.

Recommendation and future work:

Since wave energy idea, as a green energy source is still in fledgling condition, less work has been conducted on wave energy research and application on seagoing vessels. Below are a few recommendations from authors to conduct further research in this regard.

- For ensuring the viability of wave energy while the vessel is at sea, more thorough research is required on advanced fluid dynamics and wave resistance effect on the ship.
- Lot more works can be done on WITT WEC system for making it viable in the ship at sea.
- Lots of future works are to be conducted and ensure whether existing wave energy harnessing solutions are viable or not. There are far more works to be done in this field for developing and designing more efficient and suited WEC device for fitting in the vessel.
- Frictional drag effect of wave energy converters is to be vastly calculated whether they make any drawbacks or not.
- There is a vast scope of doing hard works and research for commercially and profitably implementation of large WEC technologies at near shore and port.
- Further research can be conducted in the field of designing and developing WEC technologies which are feasible to work in shallow water such as Bangladesh seabed area.

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