Arab Academy for Science, Technology and Maritime Transport

College of Engineering and Technology

<Mechanical Engineering>

B. Sc. Final Year Project

Enhancement of Wells Turbine Casing Performance

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ACKNOWLEDGMENT

We would like to thank our project supervisor's

Dr/Hassan ElGamal, Dr/Ahmed Samir & Dr/Rola Afify

For all of their effort and dedication, which helped us from the start to improve our performance and knowledge. They helped us in finding and searching for Improved duct design for a wells turbine system and inspired us to look forward to exploring this science and project further.

Also, many thanks and respect to all of the academic staff who taught us during our ten semesters working toward our B.Sc. in mechanical engineering.

We would also like to thank our parents for their constant support and continued efforts in all facets of our lives, especially in our education, which has gotten us this far.

Project Team…

ABSTRACT

The aim of the project is to generate electrical energy from wave energy (by changing the angle and length of the gate), one of the most important sources of renewable energy using Oscillating Water Column (OWC) housing. The project consists of Wave tank, Wells turbine housing and hot wire anemometer sensor.

By operating wave generator at different frequencies causes the water in the OWC moves upwards and downwards at different speeds causes the compression and expansion of the air in the housing to rotate Wells turbine. As the air speed increases the turbine rotates faster generating more electrical power.

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1. INTRODUCTION

1.1 RENEWABLA ENERGY

It is energy that is collected from renewable resources that are naturally replenished on a human timescale. It includes sources such as sunlight, wind, rain, tides, waves, and geothermal heat. Renewable energy stands in contrast to fossil fuels, which are being used far more quickly than they are being replenished.

Renewable energy often provides energy in four important areas: electricity generation, air and water heating/cooling, transportation, and rural (off-grid) energy services. About 20% of humans' global energy consumption is renewables, including almost 30% of electricity. About 8% of energy consumption is traditional biomass, but this is declining. Over 4% of energy consumption is heat energy from modern renewables, such as solar water heating, and over 6% electricity.

Globally there are over 10 million jobs associated with the renewable energy industries, with solar photovoltaic being the largest renewable employer. Renewable energy systems are rapidly becoming more efficient and cheaper and their share of total energy consumption is increasing, with a large majority of worldwide newly installed electricity capacity being renewable. In most countries, photovoltaic solar or onshore wind are the cheapest new-build electricity. [1]

1.1.1 Types of Renewable Energy Sources:

1.1.1.1 Solar Energy

Humans have been harnessing solar energy for thousands of years—to grow crops, stay warm, and dry foods. According to the National Renewable Energy Laboratory, "more energy from the sun falls on the earth in one hour than is used by everyone in the world in one year." Today, we use the sun's rays in many ways—to heat homes and businesses, to warm water, or power devices.

Figure1-1: Solar panels on the rooftops of East Austin, Texas.

Solar, or photovoltaic (PV), cells are made from silicon or other materials that transform sunlight directly into electricity. Distributed solar systems generate electricity locally for homes and businesses, either through rooftop panels or community projects that power entire neighbourhoods. Solar farms can generate power for thousands of homes, using mirrors to concentrate sunlight across acres of solar cells. Floating solar farms—or "floatovoltaics"—can be an effective use of wastewater facilities and bodies of water that aren't ecologically sensitive. Solar supplies a little more than 1 percent of U.S. electricity generation**.** But nearly a third of all new generating capacity came from solar in 2017, second only to natural gas. Solar energy systems don't produce air pollutants or greenhouse gases, and as long as they are responsibly sited, most solar panels have few environmental impacts beyond the manufacturing process.

1.1.1.2 Wind Energy

We've come a long way from old-fashioned wind mills. Today, turbines as tall as skyscrapers—with turbines nearly as wide in diameter—stand at attention around the world.

Wind energy turns a turbine's blades, which feeds an electric generator and produces electricity. Wind, which accounts for a little more than 6 percent of U.S. generation, has become the cheapest energy source in many parts of the country. Top wind power states include California, Texas, Oklahoma, Kansas, and Iowa, though turbines can be placed anywhere with high wind speeds—such as hilltops and open plains—or even offshore in open water.

1.1.1.3 Hydroelectric Power

Hydropower is the largest renewable energy source for electricity in the United States, though wind energy is soon expected to take over the lead. Hydropower relies on water—typically fast-moving water in a large river or rapidly descending water from a high point—and converts the force of that water into electricity by spinning a generator's turbine blades.

Nationally and internationally, large hydroelectric plants—or mega-dams—are often considered to be non-renewable energy. Mega-dams divert and reduce natural flows, restricting access for animal and human populations that rely on rivers. Small hydroelectric plants (an installed capacity below about 40 megawatts), carefully managed, do not tend to cause as much environmental damage, as they divert only a fraction of flow.

1.1.1.4 Biomass Energy

Biomass is organic material that comes from plants and animals, and includes crops, waste wood, and trees. When biomass is burned, the chemical energy is released as heat and can generate electricity with a steam turbine.

Biomass is often mistakenly described as a clean, renewable fuel and a greener alternative to coal and other fossil fuels for producing electricity. However, recent science shows that many forms of biomass—especially from forests—produce higher carbon emissions than fossil fuels. There are also negative consequences for biodiversity. Still, some forms of biomass energy could serve as a low-carbon option under the right circumstances. For example, sawdust and chips from sawmills that would otherwise quickly decompose and release carbon can be a low carbon energy source.

1.1.1.5 Geothermal Energy

If you've ever relaxed in a hot spring, you've used geothermal energy. The earth's core is about as hot as the sun's surface, due to the slow decay of radioactive particles in rocks at the center of the planet. Drilling deep wells brings very hot underground water to the surface as a hydrothermal resource, which is then pumped through a turbine to create electricity. Geothermal plants typically have low emissions if they pump the steam and water they use back into the reservoir. There are ways to create geothermal plants where there are not underground reservoirs, but there are concerns that they may increase the risk of an earthquake in areas already considered geological hot spots.

Figure 1-2: The Svartsengi geothermal power plant near Grindavík, Iceland.

1.1.1.6 Ocean

Tidal and wave energy is still in a developmental phase, but the ocean will always be ruled by the moon's gravity, which makes harnessing its power an attractive option. Some tidal energy approaches may harm wildlife, such as tidal barrages, which work much like dams and are located in an ocean bay or lagoon. Like tidal power, wave power relies on dam-like structures or ocean floor–anchored devices on or just below the water's surface. [2]

1.1.1.7 Marine energy

It is one of the most widely available types of renewable energy – 71% of the Earth that is covered by oceans could potentially satisfy the electricity demands of the whole world. Marine energy encompasses wave energy, tidal energy, ocean thermal energy, osmotic energy, and ocean current energy; most marine energy harnessing technologies are still in their infancy. The promising prospect of marine energy attracts worldwide attention from researchers and industry developers. This article introduces the state of the art of marine energy and discusses its economic and environmental impacts.

Marine energy is a major source of renewable energy and yet remains untapped. As the ocean covers about two-thirds of the Earth's surface, it contains a large amount of energy. Energy can be extracted from the sea exploiting several phenomena, such as salinity gradient (energy from the difference in the salt concentration between seawater and fresh water), temperature gradient, waves, and ocean currents. Among these, ocean waves have tremendous potential as a source of renewable energy. The vast amount of energy from the waves could meet an important part of the energy demand for humankind. Wave energy is enormous, reliable, and has higher energy density compared to wind power and solar power, and thus offers a good correlation between resource and demand. Waves also offer multiple locations for energy harvesting from the shoreline to deep water. There has been worldwide interest in harnessing this immense power from the ocean that can play a major part to solve our energy problems. [3]

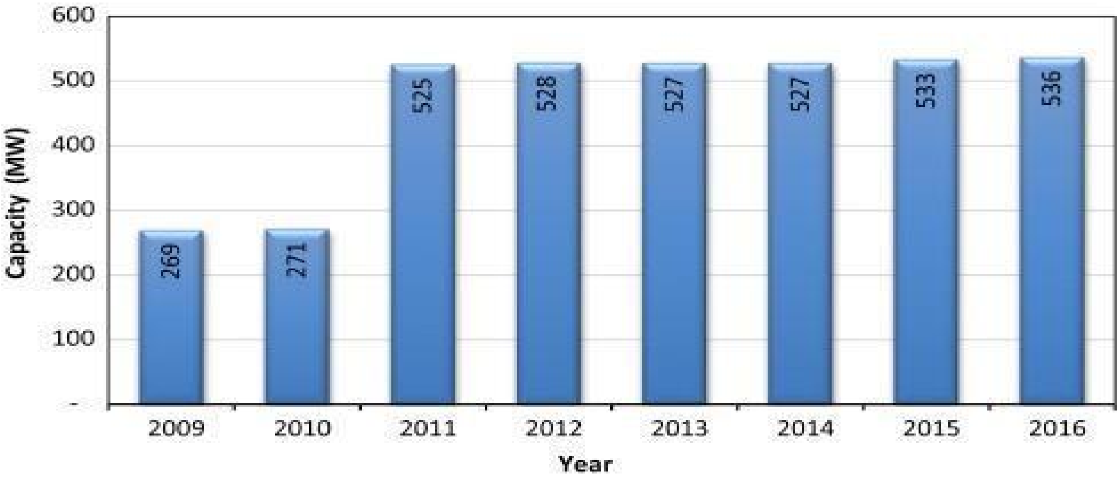


Figure1-3: Global marine energy capacity from 2009 to 2016 (Statista, 2017).

1.1.1.8 Forms of ocean energy

The oceans represent a vast and largely untapped source of energy in the form of surface waves, fluid flow, salinity gradients, and thermal differences.

Marine and Hydrokinetic (MHK) or marine energy development in U.S. and international waters includes projects using the following devices:

- Wave power converters in open coastal areas with significant waves;
- Tidal turbines placed in coastal and estuarine areas;
- In-stream turbines in fast-moving rivers;
- Ocean current turbines in areas of strong marine currents;
- Ocean thermal energy converters in deep tropical waters.[4]

Table 1-1: ***Source:*** **IEA-OES, Annual Report 2007**

From	Annual generation
Tidal energy	>300 TWh
Marine current power	>800 TWh
Osmotic power	2,000 TWh
Ocean thermal energy	10,000 TWh
Wave energy	8,000-80,000 TWh

1.2 WAVE POWER

Wave power is the capture of energy of wind waves to do useful work – for example, electricity generation. A machine that capture the wave power is a wave energy converter (WEC). Wave power is distinct from tidal power, which captures the energy of the current caused by the gravitational pull of the Sun and Moon. Waves and tides are also distinct from ocean currents which are caused by other forces including breaking waves, wind, the Coriolis effect, cabling, and differences in temperature and salinity.

Wave-power generation is not a widely employed commercial technology compared to other established renewable energy sources such as wind power, hydropower and solar power. However, there have been attempts to use this source of energy since at least 1890[1] mainly due to its high power density. As a comparison, the power density of photovoltaic panels is 1 kW/m^2 at peak solar insolation, and the power density of the wind is 1 kW/m^2 at 12 m/s; the average annual power density of the waves at e.g. San Francisco coast is 25 kW/m^2.

In 2000 the world's first commercial Wave Power Device, the Islay LIMPET was installed on the coast of Islay in Scotland and connected to the National Grid. In 2008, the first experimental multi-generator wave farm was opened in Portugal at the Aguçadoura Wave Park.

Testing is used to validate the performance and reliability of wave energy systems in open ocean. In 2021, Cal Wave Power Technologies, Inc.[5] commissioned its pilot unit device off the coast of San Diego.

- **Simplified design of Wave Power Station**

When an object bobs up and down on a ripple in a pond, it follows approximately an elliptical trajectory.

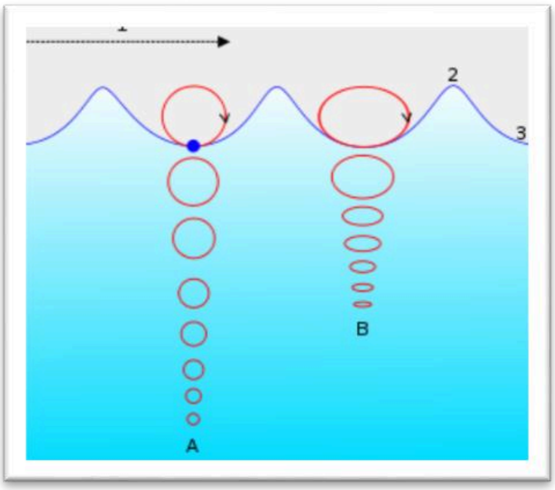


Figure 1-4: Wave Generation

Waves are generated by wind passing over the surface of the sea. As long as the waves propagate slower than the wind speed just above the waves, there is an energy transfer from the wind to the waves. Both air pressure differences between the upwind and the lee side of a wave crest, as well as friction on the water surface by the wind, making the water to go into the shear stress causes the growth of the waves.[8]

Wave height is determined by wind speed, the duration of time the wind has been blowing, fetch (the distance over which the wind excites the waves) and by the depth and topography of the seafloor (which can focus or disperse the energy of the waves). A given wind speed has a matching practical limit over which time or distance will not produce larger waves. When this limit has been reached the sea is said to be "fully developed".

In general, larger waves are more powerful but wave power is also determined by wave speed, wavelength, and water density.

Oscillatory motion is highest at the surface and diminishes exponentially with depth. However, for standing waves (clapotis) near a reflecting coast, wave energy is also present as pressure oscillations at great depth, producing microcosms. These pressure fluctuations at greater depth are too small to be interesting from the point of view of wave power.

The waves propagate on the ocean surface, and the wave energy is also transported horizontally with the group velocity. The mean transport rate of the wave energy through a vertical plane of unit width, parallel to a wave crest, is called the wave energy flux (or wave power, which must not be confused with the actual power generated by a wave power device).

1.3 OCEAN THERMAL ENERGY CONVERSION

Ocean Thermal Energy Conversion (OTEC) uses the ocean thermal gradient between cooler deep and warmer shallow or surface seawaters to run a heat engine and produce useful work, usually in the form of electricity. OTEC can operate with a very high capacity factor and so can operate in base load mode.

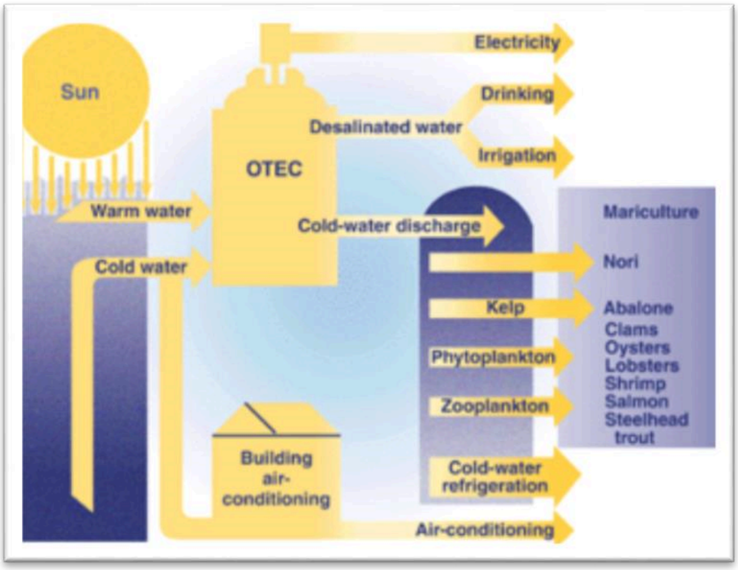


Figure 1-5: OTEC diagram and applications

The denser cold water masses, formed by ocean surface water interaction with cold atmosphere in quite specific areas of the North Atlantic and the Southern Ocean, sink into the deep sea basins and spread in entire deep ocean by the thermohaline circulation. Upwelling of cold water from the deep ocean is replenished by the down welling of cold surface sea water.

Among ocean energy sources, OTEC is one of the continuously available renewable energy resources that could contribute to base-load power supply. The resource potential for OTEC is considered to be much larger than for other ocean energy forms. Up to 88,000 TWh/yr. of power could be generated from OTEC without affecting the ocean's thermal structure.[3]

Systems may be either closed-cycle or open-cycle. Closed-cycle OTEC uses working fluids that are typically thought of as refrigerants such as ammonia or R-134a. These fluids have low boiling points, and are therefore suitable for powering the system's generator to generate electricity. The most commonly used heat cycle for OTEC to date is the Rankine cycle, using a low-pressure turbine. Open-cycle engines use vapor from the seawater itself as the working fluid.

OTEC can also supply quantities of cold water as a by-product. This can be used for air conditioning and refrigeration and the nutrient-rich deep ocean water can feed biological technologies. Another by-product is fresh water distilled from the sea.

OTEC theory was first developed in the 1880s and the first bench size demonstration model was constructed in 1926. Currently operating pilot-scale OTEC plants are located in Japan, overseen by Saga University, and Makai in Hawaii.

1.3.1 Power Cycle Types

Cold seawater is an integral part of each of the three types of OTEC systems: closed-cycle, open-cycle, and hybrid. To operate, the cold seawater must be brought to the surface. The primary approaches are active pumping and desalination. Desalinating seawater near the sea floor lowers its density, which causes it to rise to the surface.[42]

The alternative to costly pipes to bring condensing cold water to the surface is to pump vaporized low boiling point fluid into the depths to be condensed, thus reducing pumping volumes and reducing technical and environmental problems and lowering costs.[43]

1.3.1.1 Closed-cycle

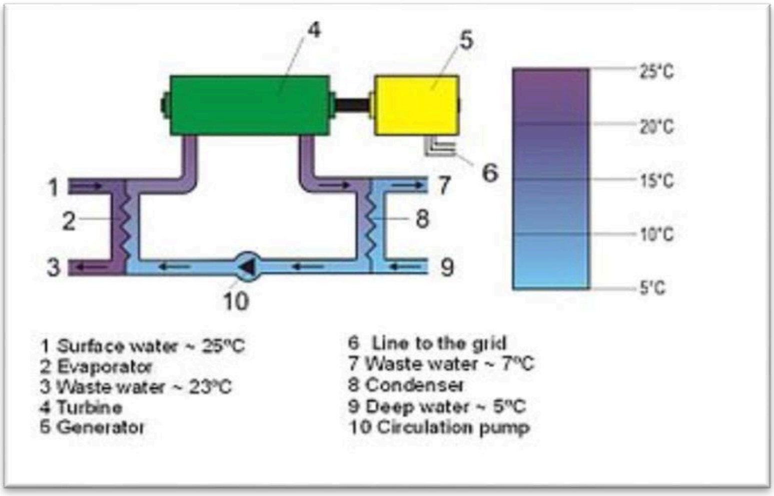


Figure 1-6: Diagram of a closed cycle OTEC plant

Closed-cycle systems use fluid with a low boiling point, such as ammonia (having a boiling point around -33°C at atmospheric pressure), to power a turbine to generate electricity. Warm surface seawater is pumped through a heat exchanger to vaporize the fluid. The expanding vapour turns the turbo-generator. Cold water, pumped through a second heat exchanger, condenses the vapour into a liquid, which is then recycled through the system.

In 1979, the Natural Energy Laboratory and several private-sector partners developed the "mini OTEC" experiment, which achieved the first successful at-sea production of net electrical power from closed-cycle OTEC.[44] The mini OTEC vessel was moored 1.5 miles (2.4 km) off the Hawaiian coast and produced enough net electricity to illuminate the ship's light bulbs and run its computers and television.

1.3.1.2 Open-Cycle

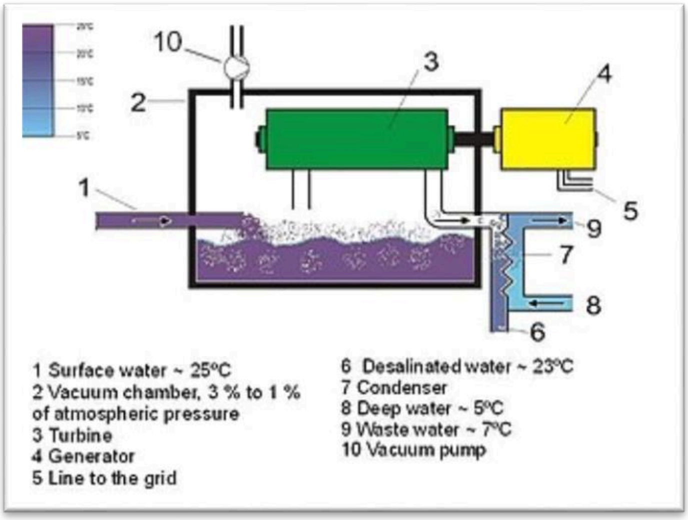


Figure 1-7: Diagram of an open cycle OTEC plant

Open-cycle OTEC uses warm surface water directly to make electricity. The warm seawater is first pumped into a low-pressure container, which causes it to boil. In some schemes, the expanding vapor drives a low-pressure turbine attached to an electrical generator. The vapor, which has left its salt and other contaminants in the low-pressure container, is pure fresh water. It is condensed into a liquid by exposure to cold temperatures from deep-ocean water. This method produces desalinized fresh water, suitable for drinking water, irrigation or aquaculture.

In other schemes, the rising vapor is used in a gas lift technique of lifting water to significant heights. Depending on the embodiment, such vapor lift pump techniques generate power from a hydroelectric turbine either before or after the pump is used.

In 1984, the *Solar Energy Research Institute* (now known as the National Renewable Energy Laboratory) developed a vertical-spout evaporator to convert warm seawater into low-pressure steam for open-cycle plants. Conversion efficiencies were as high as 97% for seawater-tosteam conversion (overall steam production would only be a few percent of the incoming water). In May 1993, an open-cycle OTEC plant at Keahole Point, Hawaii, produced close to 80 kW of electricity during a net power-producing experiment.[47] This broke the record of 40 kW set by a Japanese system in 1982.

1.3.1.3 Hybrid Cycle

A hybrid cycle combines the features of the closed- and open-cycle systems. In a hybrid, warm seawater enters a vacuum chamber and is flash-evaporated, similar to the open-cycle evaporation process. The steam vaporizes the ammonia working fluid of a closed-cycle loop on the other side of an ammonia vaporizer. The vaporized fluid then drives a turbine to produce electricity. The steam condenses within the heat exchanger and provides desalinated water (see heat pipe).

1.3.1.4 Working Fluids

A popular choice of working fluid is ammonia, which has superior transport properties, easy availability, and low cost. Ammonia, however, is toxic and flammable. Fluorinated carbons such as CFCs and HCFCs are not toxic or flammable, but they contribute to ozone layer depletion. Hydrocarbons too are good candidates, but they are highly flammable; in addition, this would create competition for use of them directly as fuels. The power plant size is dependent upon the vapor pressure of the working fluid. With increasing vapor pressure, the size of the turbine and heat exchangers decreases while the wall thickness of the pipe and heat exchangers increase to endure high pressure especially on the evaporator side.

1.4 THE OFFICE OF ENERGY EFFICIENCY AND RENEWABLE ENERGY (EERE)

The Office of Energy Efficiency and Renewable Energy (EERE) is an office within the United States Department of Energy. Formed from other energy agencies after the 1973 energy crisis, EERE is led by the Assistant Secretary of Energy Efficiency and Renewable Energy (Assistant Secretary), who is appointed by the President of the United States and confirmed by the U.S. Senate. Kelly Speaks-Backman was appointed Acting Assistant Secretary in January 2021.

EERE’s mission is to drive the research, development, demonstration, and deployment of innovative technologies, systems, and practices that will:

1. help transition Americans to a 100% clean energy economy no later than 2050 and
2. ensure the clean energy economy benefits all Americans.

1.4.1 Renewable energy sector:

The Solar Energy Technologies Office, also known as the SunShot Initiative, funds cooperative research, development, demonstration, and deployment projects by private companies, universities, state and local governments, nonprofit organizations, and national laboratories. It focuses on photovoltaics, concentrating solar power, soft costs (the nonhardware costs of solar), commercializing technologies, and integrating solar with the grid. The Geothermal Technologies Office supports research and development for geothermal technologies. The Wind Energy Technologies Office conducts research and development activities in land- based and offshore wind power and works with national laboratories, universities, laboratories, and industries. The Water Power Program researches, tests, evaluates, and develops hydropower and hydrokinetic energy technologies.

1.4.2 World energy consumption

World energy supply and consumption is global production and preparation of fuel, generation of electricity, energy transport and energy consumption. It is a basic part of economic activity. It does not include energy from food

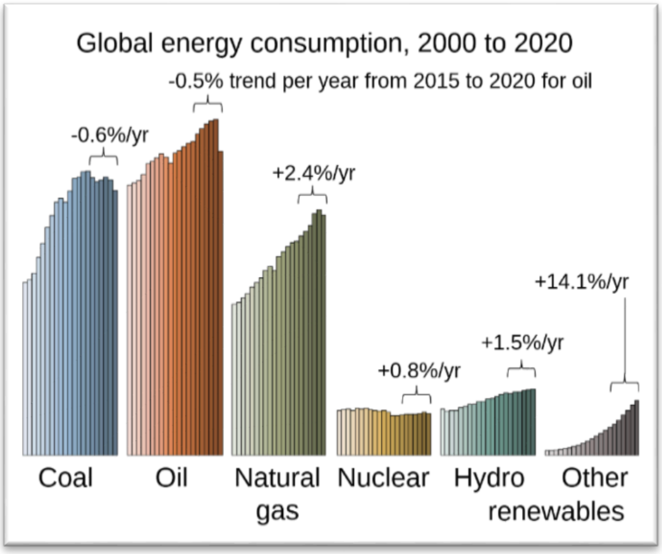


Figure 1-8: Global Energy Consumption

Coal, oil, and natural gas remain the primary global energy sources even as renewables have begun rapidly increasing.

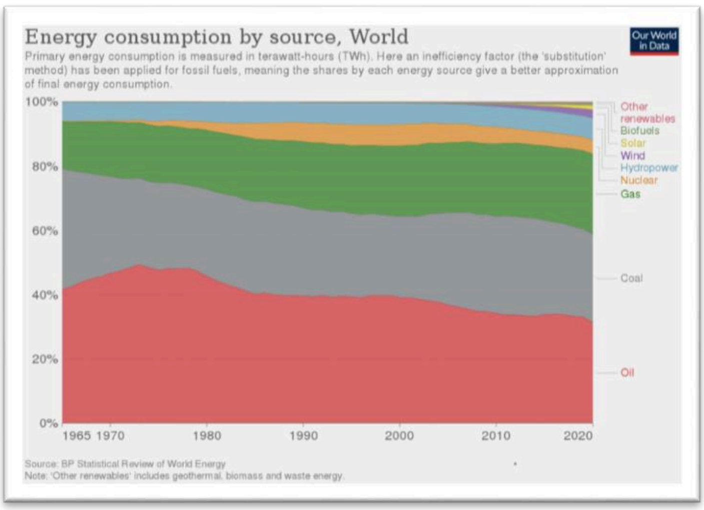


Figure 1-9: World energy mix, 1965 to 2020

Many countries publish statistics on the energy supply and consumption of either their own country, of other countries of interest, or of all countries combined in one chart. One of the largest organizations in this field, the International Energy Agency (IEA), publishes yearly comprehensive energy data. This collection of energy balances is very large. This article provides a brief description of energy supply and consumption, using statistics summarized in tables, of the countries and regions that produce and consume most. Energy production is 80% fossil. Half of that is produced by China, the United States and the Arab states of the Persian Gulf. The Gulf States and Russia export most of their production, largely to the European Union and China where not enough energy is produced to satisfy demand. Energy production increases slowly, except for solar and wind energy which grows more than 20% per year.

1.5.1 Primary Energy

Primary energy sources are transformed by the energy sector to generate energy carriers.

Produced energy, for instance crude oil, is processed to make it suitable for consumption by end users. The supply chain between production and final consumption involves many conversion activities and much trade and transport among countries, causing a loss of one quarter of energy before it is consumed.

Energy consumption per person in North America is very high while in developing countries it is low and more renewable. There was a significant decline in energy usage worldwide caused by the COVID-19 pandemic, notably in the iron and steel industry as demand for new construction shrank. To reach levels similar to that in 2019, there would need to be an increase in the global demand for manufactured goods by the iron and steel industry

Worldwide carbon dioxide emissions from fossil fuels was 38 gigatons in 2019. In view of contemporary energy policy of countries, the IEA expects that worldwide energy consumption in 2040 will have increased more than a quarter and that the goal, set in the Paris Agreement to limit climate change, will not nearly be reached. Several scenarios to achieve the goal are developed.

This is the worldwide production of energy, extracted or captured directly from natural sources. In energy statistics primary energy (PE) refers to the first stage where energy enters the supply chain before any further conversion or transformation process.

Energy production is usually classified as:

- Fossil, using coal, crude oil, and natural gas.
- Nuclear, using uranium.

- Renewable, using biomass, geothermal, hydropower, solar, tidal, wave, wind, and among others.

The table lists the worldwide PE and the countries/regions producing most (90%) of that. The amounts are rounded and given in million tons of oil equivalent per year (1 Mtoe = 11.63 TWh, 1 TWh = 109 kWh). The data are of 2018.

Table 1-2: List of the worldwide PE

	Total	Coal	Oil & Gas	Nuclear	Renewable
China	2560	1860	325	77	300
United States	2170	369	1400	219	180
Middle East	2040	1	2030	2	4
Russia	1484	240	1165	54	25
Africa	1169	157	611	3	397
Europe	1111	171	398	244	296
India	574	289	67	10	208
Canada	529	31	422	26	50
Indonesia	451	288	102	0	61
Australia	412	287	115	0	9
Brazil	296	2	160	4	129
Kazakhstan	178	49	128	0	1
Mexico	159	7	132	4	16
World	**14420**	**3890**	**7850**	**707**	**1972**

In the Middle East, the Persian Gulf states of Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates produced the most. A small part came from Bahrain, Jordan, Lebanon, Syria, and Yemen.

The top producers in Africa were Nigeria (256), South Africa (158), Algeria (156), and Angola
(85).

In Europe, Norway (207, oil and gas), France (135, mainly nuclear), the United Kingdom (123), Germany (112), Poland (62, mainly coal), and the Netherlands (36, mainly natural gas) produced the most of the world's renewable energy supply, 68% is generated with biofuel and waste, mostly in developing countries, 18% is generated with hydropower and 14% with other renewables.

1.4.2 Energy conversion and trade

Table 1-3

	Export minus Import
Mid-East	1245
Russia	701
Africa	319
Australia	280
Canada	228
Indonesia	220
Norway	177
United States	-80
Korea	-252
India	-347
Japan	-387
China	-733
Europe	-985

Primary energy is converted in many ways to energy carriers, also known as secondary energy.

- Coal mainly goes to thermal power stations. Coke is derived by destructive distillation of bituminous coal.
- Crude oil goes mainly to oil refineries
- Natural-gas goes to natural-gas processing plants to remove contaminants such as water, carbon dioxide and hydrogen sulfide, and to adjust the heating value. It is used as fuel gas, also in thermal power stations.
- Nuclear reaction heat is used in thermal power stations.
- Biomass is used directly or converted to biofuel.

Much primary and converted energy is traded among countries, about 5800 Mtoe worldwide, mostly oil and gas. The table lists countries/regions with large difference of export and import. A negative value indicates that much energy import is needed for the economy. The quantities are expressed in Mtoe/a and the data are of 2018. Big transport goes by tanker ship, tank truck, LNG carrier, rail freight transport, pipeline and by electric power transmission.

Table 1-4

Location		TES		PE
China	3210		2560	
Europe	1984		1111	
India	919		574	
Mid-East	760		2040	
Russia	760		1484	
Japan	426		50	
S-Korea	282		45	
Canada	298		529	
World	**14280**		**14420**	

1..4.3 Total Energy Supply (TES)

Total Energy Supply (TES) indicates the sum of production and imports subtracting exports and storage changes. For the whole world TES nearly equals primary energy PE because imports and exports cancel out, but for countries/regions TES and PE differ in quantity, and also in quality as secondary energy is involved, e.g., import of an oil refinery product. TES is all energy required to supply energy for end users. The table lists TES and PE for some countries/regions where these differ much, and worldwide. The amounts are rounded and given in Mtoe. The data are of 2018.

Table 1-5: History (TWh)

Year	**Total energy supply (TES)**	**Final energy consumption1**	**Electricity generation**
1973	71,013 (Mtoe 6,106)	54,335 (Mtoe 4,672)	6,129

1990	102,569	–	11,821
2000	117,687	–	15,395
2010	147,899 (Mtoe 12,717)	100,914 (Mtoe 8,677)	21,431
2011	152,504 (Mtoe 13,113)	103,716 (Mtoe 8,918)	22,126
2012	155,505 (Mtoe 13,371)	104,426 (Mtoe 8,979)	22,668
2013	157,482 (Mtoe 13,541)	108,171 (Mtoe 9,301)	23,322
2014	155,481 (Mtoe 13,369)	109,613 (Mtoe 9,425)	23,816
2015	158,715 (Mtoe 13,647)	109,136 (Mtoe 9,384)	
2017	162,494 (Mtoe 13,972)	113,009 (Mtoe 9,717)	25,606

It is converted from Mtoe into TWh (1 Mtoe = 11.63 TWh) and from Quad BTU into TWh (1 Quad BTU = 293.07 TWh) 25% of worldwide primary production is used for conversion and transport, and 6% for non- energy products like lubricants, asphalt, and petrochemicals. 69% remains for end users. Most of the energy lost by conversion occurs in thermal electricity plants and the energy industry's own use.

One needs to bear in mind that there are different qualities of energy. Heat, especially at a relatively low temperature, is low-quality energy, whereas electricity is high-quality energy. It takes around 3 kWh of heat to produce 1 kWh of electricity. But by the same token, a kilowatt- hour of this high-quality electricity can be used to pump several kilowatthours of heat into a building using a heat pump. And electricity can be used in many ways in which heat cannot. So the "loss" of energy incurred when generating electricity is not the same as a loss due to, say, resistance in power lines.

1.4.4 Total Final Consumption (TFC)

Total final consumption (TFC) is the worldwide consumption of energy by end-users (whereas primary energy consumption (Eurostat) or total energy supply (IEA) is total energy demand and thus also includes what the energy sector uses itself and transformation and distribution losses). This energy consists of fuel (78%) and electricity (22%). The tables list amounts, expressed in million tons of oil equivalent per year (1 Mtoe = 11.63 TWh) and how much of these is renewable energy. Non-energy products are not considered here. The data are of 2018.

1.4.5 Fuel

1. Fossil: natural gas, fuel derived from petroleum (LPG, gasoline, kerosene, gas/diesel, fuel oil), from coal (anthracite, bituminous coal, coke, blast furnace gas).
2. The amounts are based on lower heating value.

The first able lists final consumption in the countries/regions which use most (85%), and per person. In developing countries fuel consumption per person is low and more renewable. Canada, Venezuela and Brazil generate most electricity with hydropower.

Table 1-6: Final consumption in most using countries and per person.

Country	Fuel Mtoe	of which renewable	Electricity Mtoe	of which renewable	TFC pp toe
China	1436	6%	555	30%	1.4
United States	1106	8%	339	19%	4.4
Europe	982	11%	309	39%	2.5
Africa	531	58%	57	23%	0.5
India	487	32%	104	25%	0.4
Russia	369	1%	65	26%	3.0
Japan	201	3%	81	19%	2.2
Brazil	166	38%	45	78%	1.0
Indonesia	126	21%	22	14%	0.6
Canada	139	8%	45	83%	5.0
Iran	147	0%	22	6%	2.1
Mexico	95	7%	25	18%	1.0
S-Korea	85	5%	46	5%	2.6
Australia	60	7%	18	21%	3.2
Argentina	42	7%	11	27%	1.2
Venezuela	20	3%	6	88%	0.9

World	**7050**	**14%**	**1970**	**30%**	**1.2**

In Africa 32 of the 48 nations are declared to be in an energy crisis by the World Bank.

The next table shows countries consuming most (85%) in Europe.

Table 1-7: Countries consuming most (85%) in Europe.

Country	Fuel Mtoe	of which renewable	Electricity Mtoe	of which renewable
Germany	156	10%	45	46%
France	100	12%	38	21%
United Kingdom	95	5%	26	40%
Italy	87	9%	25	39%
Spain	60	10%	21	43%
Poland	58	12%	12	16%
Ukraine	38	5%	10	12%
Netherlands	36	4%	9	16%
Belgium	26	8%	7	23%
Sweden	20	35%	11	72%
Austria	20	19%	5	86%
Romania	19	20%	4	57%
Finland	18	34%	7	39%
Portugal	11	20%	4	67%
Denmark	11	15%	3	71%
Norway	8	16%	10	100%

1.4.6 IEA Scenarios

In World Energy Outlook 2021 (WEO) the IEA presents four scenarios based on the computer Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC). Net Zero by 2050 (NZE) is an integral part of the WEO.

14.6.1 In Stated Policies Scenario (STEPS)

IEA assesses the likely effects of 2021 policy settings. This would lead to global average temperatures still rising when they hit 2.6 °C above pre-industrial levels in 2100.

1.4.6.2 The Announced Pledges Scenario (APS)

assumes that all climate commitments will be met in full and on time. Average temperature will rise to around 2.1 °C by 2100 and continues to increase.

1.4.6.3 The Sustainable Development Scenario (SDS)

assumes in addition to APS a surge in clean energy policies and investment. Advanced economies reach net zero emissions by 2050, China around 2060, and all other countries by 2070 at the latest. Then temperature will peak at 1.7 °C by 2050 and could decline to 1.5 °C by 2100. In 2050 energy supply will be 55% renewable. Table A.5, A.6 Electricity generation will be 58% renewable and 8% nuclear.

1.4.7 Alternative

Global electricity generation from renewable energy sources will reach 88% by 2040 and 100% by 2050 in the alternative scenarios. "New" renewables — mainly wind, solar and geothermal energy — will contribute 83% of the total electricity generated. The average annual investment required between 2015 and 2050, including costs for additional power plants to produce hydrogen and synthetic fuels and for plant replacement, will be around $1.4 trillion

Shifts from domestic aviation to rail and from road to rail are needed. Passenger car use must decrease in the OECD countries (but increase in developing world regions) after 2020. The passenger car use decline will be partly compensated by strong increase in public transport rail and bus systems.

CO2 emission can reduce from 32 Gt in 2015 to 7 Gt (+2.0 Scenario) or 2.7 Gt (+1.5 Scenario) in 2040, and to zero in 2050.

1.5 LIST OF POWER STATION

The following list contain most power stations run on wave power.

Wave farms are classified into 6 types based on the technology used, such as surfacefollowing attenuator, point absorber, oscillating wave surge converter, oscillating water column, overtopping/terminator, submerged pressure differential, bulge wave device, and rotating mass.

Table 1-8: List of wave power station

Station	Country	Capacity (MW)	TYPE	COMM.
Ada foah wave farm	GHANA	0.4	POINT ABSORBER	2016
Agucadoura wave farm	PORTUGAL	2.25	Surfacefollowing attenuator	2008
Azura	UNITED STATES	0.02	POINT ASBORBER	2015
BOLT Lifesaver	UNITED STATES	0.03	POINT ASBORBER	2016
Islay Limpet	United kingdom	0.5	Oscillating water column	2000
Mutriku breakwater wave plant	SPAIN	0.3	Oscillating water column	2009

1.6 LIST OF WAVE POWER PROJECTS

Table 1-9: List of wave power projects.

PROJECT	STATION	COUNTRY	TYPE	COMM	LOCAT	TECH
150 KW Indian wave energy program (1)	IIT Madres	VIZHINJAM , INDIA	OWC	1991	Bottom standing near shore	Electric to grid
Albatern waveNET (2)	ALBATERN	SCOTLAND, UK	MULTI POINT ABSORBER ARRAY	2010	Offshore	
AMOG, AEP WEC (3)	FLAMOUTH	CORNWALL ,UK	SURFACE DYNAMIC VIBRATION ABSORBER	2019	OFFSHORE	ELECTRIC

AquaBuOY (4)	FINAVERA WIND ENERGY , LATER SSE RENEWABLES LIMITED	IRELAND-CANADA – SCOTLAND	BUOY	2003	OFFSHORE	HYDROELECTRIC TRUBINE
ATMOCEAN(5)	ATMOCEAN INC.	USA	POINT ABSORBER ARRAY	2006	NEARSHORE & OFFSHORE	PUMP- TO-SHORE
AWS-III (6)	AWS OCEAN ENERGY	UK (SCOTLAND)	SURFACE – FOLLOWING ATTENUATOR	2010	OFF SHORE	AIR TURBINE
CCEL (7)	ZYBA RENEWABLES	UNITED KINGDOM	OSCILLATING WAVE SURGE CONVERTER	2015	NEARSHORE & OFFSHORE	HYDRAULIC
CRESTWING (8)	CRESTWING APS	DENMARK	SURFACFOLLOWING ATTENUATOR	2011	OFFSHORE	MECHANICAL

1.6.1 150KW Indian Wave Energy Program

THE wave energy group at ocean engineering, Indian institute of technology (IIT) madras, funded by the department of ocean development, government of India built, operated, instrumented, and tested a 150 kw owc wave energy nearshore bottom standing caisson with different turbines over a period of multiple decades.

Since the wave power in the equatorial region where this device was tested was low about 13 kw/m, the choice was for a multi-functional breakwater unit that could provide a safe harbor for fishing vessels and produce power more economically by sharing the costs of the structure. Even though the power demonstrated was electric pumped to the grid, the group has researched directly producing desalinated water and thermal storage using refrigeration. These technologies alleviate the need for an electric grid and demonstrate alternate power requirements appropriate for the location.

Figure 1-10: 150 KW Indian wave energy program

1.6.2 Albatern Communit

albatern are working with their iteration devices with a 14-week deployment on a Scottish fishfarm site in 2014 and a 6-unit array deployment for full characterization at kishorn port in 2015. Initially working with smaller devices and arrays, the company is targeting off grid markets where diesel generation is presently used in offshore fishfarms, coastal communities and long endurance scientific platforms. Demonstration projects are under development for fishfarm sites and an island community.

1.6.3 AMOG, AEP WEC

AMOG are progressing through a technology readiness level stage gated approach applying oil and gas offshore experience to the wave energy sector .A 1/3rd scale device was successfully deployed in the European 2019 summer at FaBTest .Financial support for the deployment came from the marine-scheme under the European union regional development company .The device was built by mainstay marine in wales installed by KML from SW England and tank tested at AMC/Uni of Tasmania and Uni of Plymouth .It has a barge shaped hull with an inair pendulum tuned to absorb the wave motion, rather than the hull .A PTO is situated on top of the pendulum with electricity generated and dissipated locally through immersion heaters submerged in the seawater . The device’s maximum rating is 75 kw.

Figure 1-11: 150 KW Indian wave energy program

1.6.4 AquaBuOY

In 2009 Finavera Renewables surrendered its wave energy permits from FERC. In July 2010 Finavera announced that it had entered into a definitive agreement to sell all assets and intellectual property related to the AquaBuOY wave energy technology.

1.6.5 ATMOCEAN

The Atmocean array consists of 15, 3m diameter surface buoys. Instead of direct seafloor connections, the entire array is anchored at 6 points. Each buoy uses passing waves to pump seawater into the system and send it onshore where it goes directly into an R/O desalination process without the need for an external energy source. Advantages of smaller modular system include using standard shipping containers and small boat operations. Two full scale trials were deployed off the coast of Ilo Perú in 2015. Additional are set for 2017.

Figure 1-12: single atmocean pump being deployed in ilo

1.7 TURBINS

A turbine is a rotating mechanical device that extracts energy from a fluid flow and converts it into useful work. The work produced by the turbine can be used in combination with a generator to generate electrical power. A turbine is a turbomachine with at least one moving part called a rotor assembly, which is a shaft or drum with blades attached. Moving fluid acts on the blades, causing them to move and transmit rotational energy to the rotor. [10] Based on the type of fluid, turbines are classified as steam, hydro, or air turbines.

1.7.1 Classifications of Turbines:

1.7.1.1 Steam Turbine

A steam turbine (Figure 1-13) is a device that extracts thermal energy from the steam and converts it to mechanical work on a rotating output shaft. [11] A steam turbine consists of a boiler **(**steam generator**)**, turbine**,** condenser**,** feed pump, and various auxiliary devices in its simplest form. Unlike reciprocating engines, for instance, compression, heating, and expansion are continuous and occur simultaneously.

Since the steam turbine is a rotary heat engine, it is particularly suited to drive an electrical generator. Note that about **90%** of all electricity generation in the world is by use of steam turbines. Steam turbine was invented in 1884 by Sir Charles Parsons**,** whose first model was connected to a dynamo that generated 7.5 kW (10 hp) of electricity. The steam turbine is a common feature of all modern and also future thermal power plants. Also, the power production of fusion power plants is based on the use of conventional steam turbines. [12]

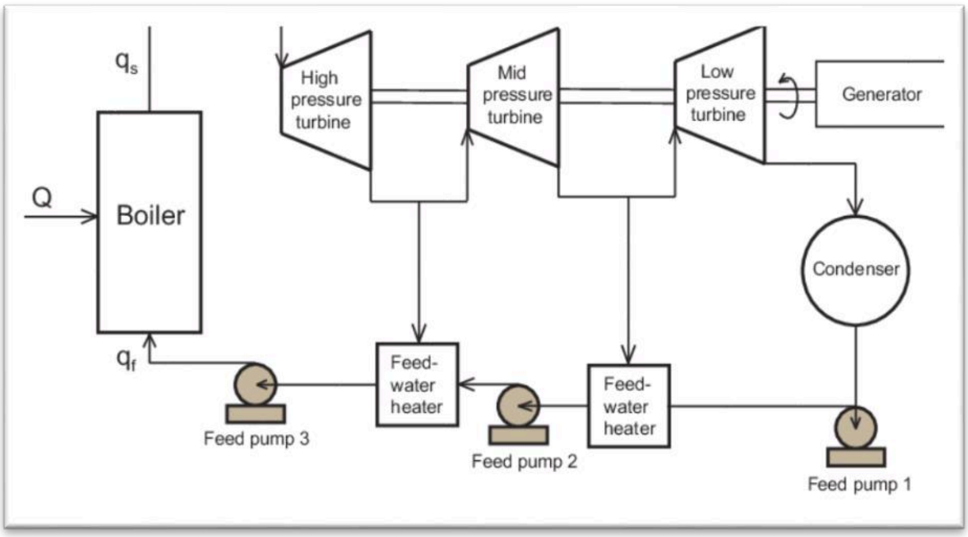


Figure1-13: Schematic illustration of steam turbine power generation system.

1.7.1.2 Hydro Turbine

Hydro turbines (Figure 1-14) are devices used in hydroelectric generation plants that transfer the energy from moving water to a rotating shaft to generate electricity. These turbines rotate or spin as a response to water being introduced to their blades. These turbines are essential in the area of hydropower "the process of generating power from water." [13]

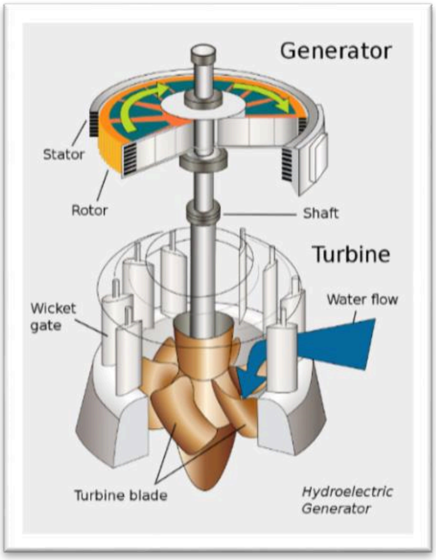


Figure1-14: Hydro Turbine.

Hydro turbines can be classified based on how water flows through the turbine itself. When passed through a turbine, water can take a variety of different paths. This leads to three categories of water flow through turbines: [14]

- Axial Flow: Water flows through the turbine parallel to the axis of rotation.
- Radial Flow: Water flows through the turbine perpendicular to the axis of rotation.
- Mixed Flow: Water flows through in a combination of both radial and axial flows.

1.7.1.3 Air Turbine

An air turbine is a turbine driven by airflow.

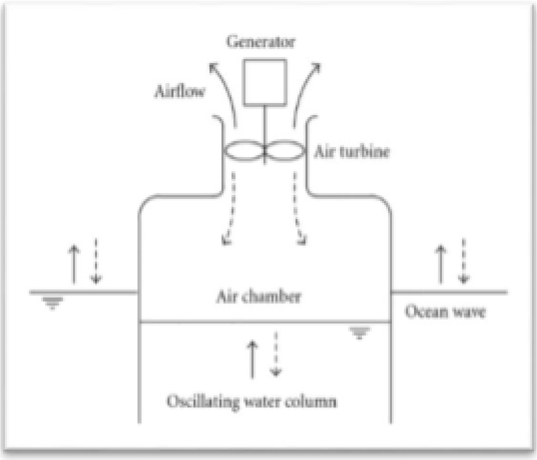
Various forms include:

- Wind turbine: a renewable energy source.
- Gas turbine: a type of internal combustion engine.
- Ram air turbine (RAT): an emergency power system for aircraft.
- Small air turbines, used as high-speed pneumatic motors in tools such as dentist's drill. The oscillating water column (OWC) is among the first types of wave energy converter to be developed and deployed into the sea, and one of the most successful devices. The OWC device comprises a partly submerged concrete or steel

chamber, fixed or floating and open below the water surface, inside which air is trapped above the water-free surface.

The oscillating motion of the internal free surface produced by the incident waves makes the air flow through a turbine that drives an electrical generator (Figure 1-17). [15]

The energy conversion process in OWC plant (Figure 1-18) occurs in three phases. Initially, the oscillation of sea surface is converted to pressure energy in the air chamber and the air turbine converts the pressure energy into mechanical shaft power (this system is also known as power take off mechanism). Finally, the generator connected to the turbine converts the shaft power to usable electrical power. [16]



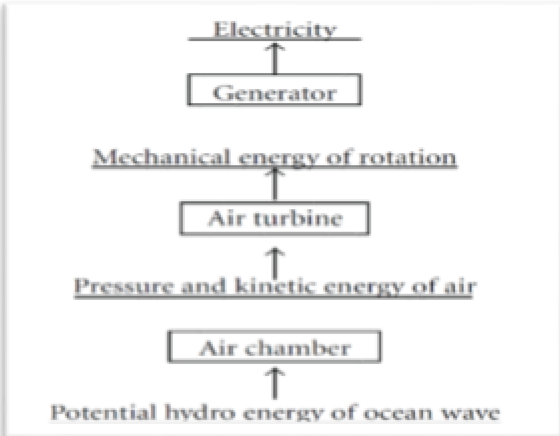


Figure1-15: Schematic view of OWC. **Figure1-16: Energy conversion chain of OWC.**

Most of the OWC systems for wave energy conversion used till date mainly relied on two basic types of air turbines: the wells turbine and the impulse turbine (Figure 1-19). In the case of impulse turbines, the total pressure energy of the fluid is converted to kinetic energy before hitting the rotor blades, whereas in the case of wells turbines, the pressure and kinetic energy both change as the water flow through the rotor blades. [16]

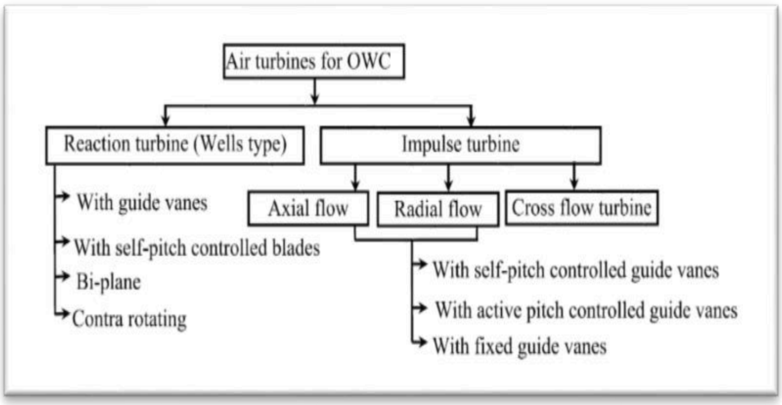


Figure1-17: classification of air turbines.

1.7.1.3.1 Impulse Turbine

The main difference between a wells turbine and an impulse turbine is the way energy transfer occurs in the rotor. Impulse turbines are classified based on the direction of airflow through them: axial and radial. An impulse turbine can be made bidirectional flow turbine using guide vanes on both sides of the rotor. Airflow deflected by the guide vanes hits the rotor blade and gives "impulse" to the turbine. Because of the symmetrical nature of the guide vanes and rotor blade, the turbine always rotates in the same direction irrespective of the direction of airflow. This type of turbine is also known as a self-rectifying turbine. Moreover, guide vanes can be classified as fixed, self-pitch-controlled, and link mechanism types. [17]

Axial turbines are popular in both unidirectional and bidirectional flows because of their simplicity and ease of operation. However, axial turbines produce high axial thrust, which leads to bearing fatigue. Radial turbines produce less axial thrust compared to axial turbines. Moreover, the radial turbine's torque is large due to its radial configuration. [17]

1.7.1.3.1.1 Axial Turbine

The impulse turbine with self-pitch-controlled guide vanes (Figure 1-20) has guide vanes on both sides of the rotor so as to operate efficiently in an oscillating flow. They are set by pivots on the casing wall. The pivots are located at the end of the guide vane chord, close to the rotor, so that guide vanes can move around the pivot due to an aerodynamic moment caused by oscillating airflow. Every vane on one side of the rotor is connected by a link outside the casing to a vane on the other side of the rotor, (Figure 1-21). This turbine (diameter of 1.0 m) has been constructed by NIOT, India. [17]

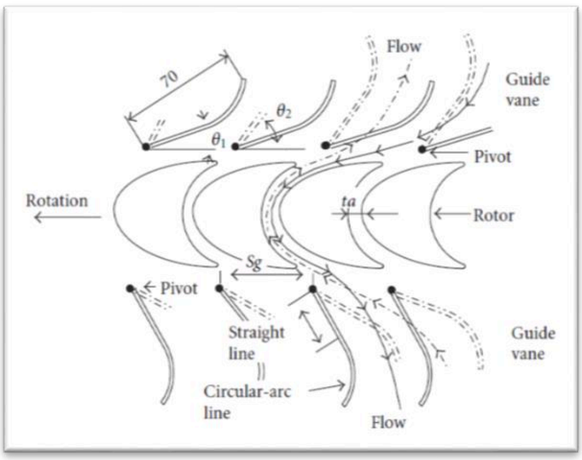


Figure 1-18: Schematic view of Impulse turbine with self-pitch-controlled guide vanes (ISGV).

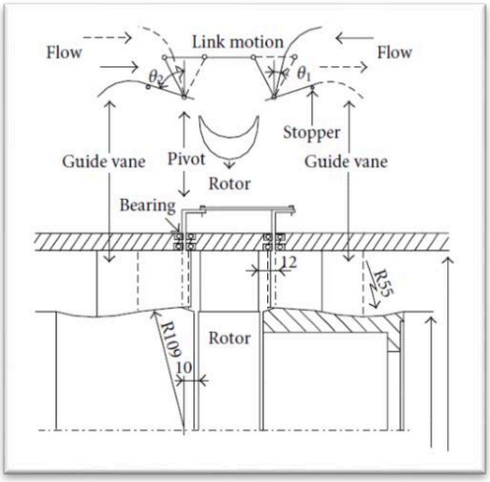


Figure 1-19: self-pitch-controlled guide vanes connected by links.

At NIOT plant, the total efficiency of the plant with this turbine was more than three times of the Wells turbine. In recent years, the impulse turbine with active-pitch controlled guide vanes by use of a hydraulic actuator has been proposed and tested. [17]

The impulse turbine with fixed guide vanes is represented in (Figure 1-22). The turbine configuration is an impulse type having fixed guide vanes both upstream and downstream, and these geometries are symmetrical with respect to the rotor centerline. This turbine has been installed in a floating OWC device "Backward Bent Duct Buoy," (Figure 1-23). [17]

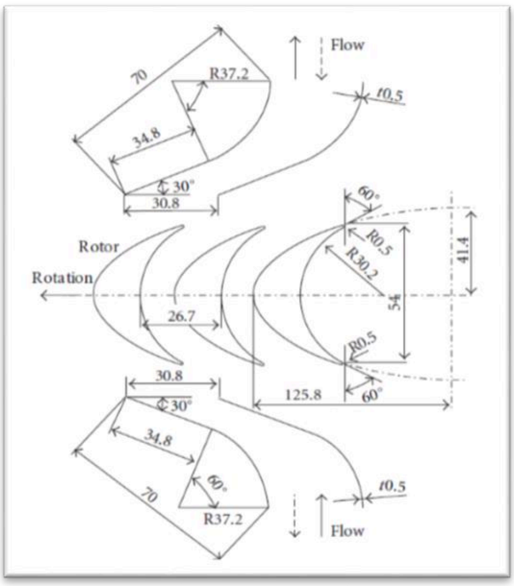


Figure 1-20: Impulse turbine with fixed guide vanes (IFGV).

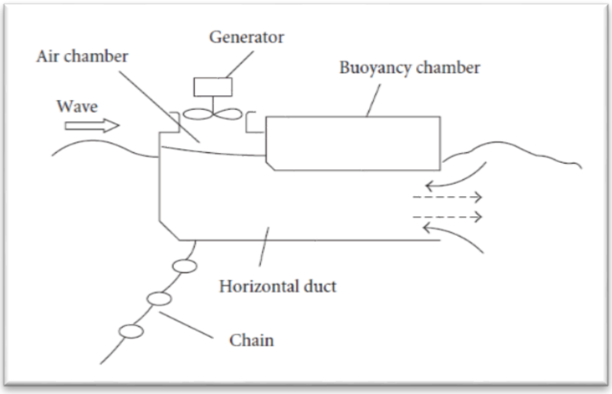


Figure 1-21: Floating-type OWC device "Backward Bent Duct Buoy."

1.7.1.3.1.2 Radial Turbine

The impulse type radial turbine is represented in (Figure 1-24). The efficiency of the turbine seems to be higher according to the previous studies, though detailed turbine characteristics are not found in the literature. However, according to recent research, the efficiency is not so good. The authors propose a radial turbine with active-controlled guide vanes for wave energy conversion to solve this disadvantage. [17]

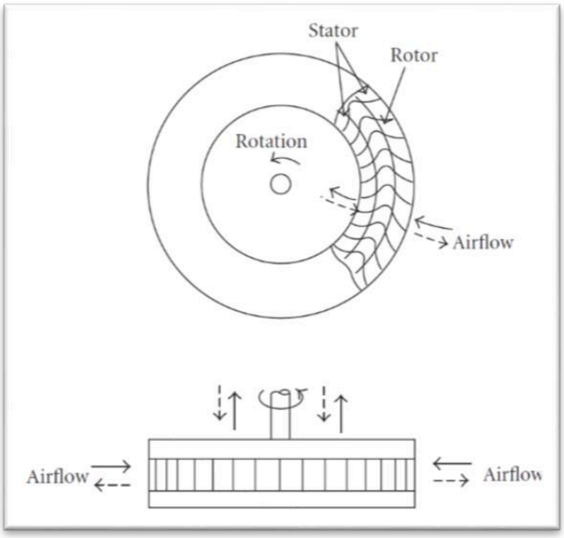


Figure 1-22: Radial turbine with fixed guide vanes.

1.7.1.3.2 Wells Turbine

The Wells turbine (Figure 1-25) is a type of axial flow reaction turbine that uses oscillating airflow to extract wave energy. The turbine is built up of symmetric airfoil type blades that are arranged around a central hub and rotate in one direction regardless of airflow direction. It has a rotational speed limited by the blade tip velocity approaching toward the speed of sound. The turbine is connected to the generator and can be used with or without guide vanes. [16]

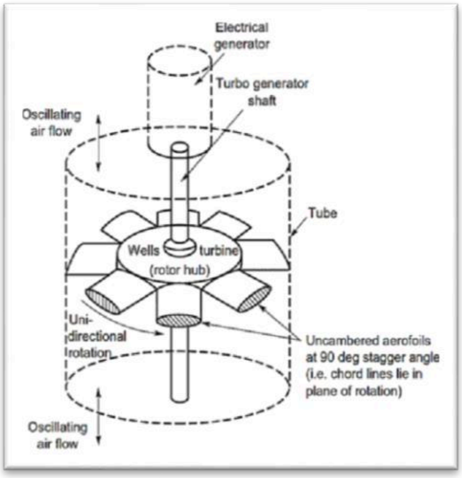


Figure 1-23: Schematic view of wells turbine.

1.7.1.3.2.1 Principle of operation of wells turbine

The Wells turbine works on the general aerodynamics theory of airfoil. Blades are set at 90° stagger angle. The absolute velocity of air hits the blade axially and the tangential velocity of the blade acts in a direction parallel to the plane of rotation. The relative velocity W acting at an angle α (angle of attack) to the blade causes a lift force L perpendicular to the direction of W and a drag force D in the direction of W (Figure 1-26). [16]

This lift and drag force can be resolved in tangential and axial direction

$$F_{tan} = L\ sin(\alpha) - D\ \cos(\alpha)$$

$$F_x = L\ cos(\alpha) + D\ \sin(\alpha)$$

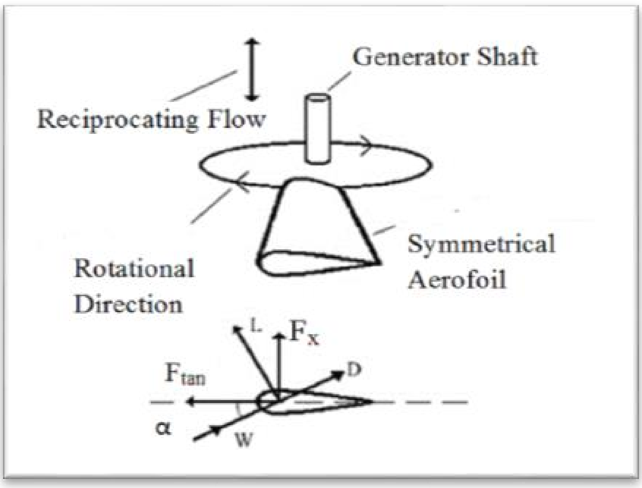


Figure 1-24: Principle of operation of Wells turbine.

The direction of tangential force is always the same for any airflow direction. As a result, the turbine's rotational direction is always the same. The lift and drag forces on the airfoil rise for any actual fluid up to a particular angle of attack(α), after which the flow splits around the airfoil. The angle at which flow separates from the airfoil is known as the stall angle. Beyond the stall angle, the lift force decreases and drag force increases significantly. As a result, the tangential force on the rotor reduces, resulting in lower efficiency. The operational range of a Wells turbine is thus limited by the angle of stall. [16]

1.7.3.2.2 Parameters of Wells Turbine

Some of the main geometric parameters that affect the performance of wells turbine are solidity, hub-to-tip ratio, aspect ratio, and tip clearance. The parameters are described analytically in Table 1-1. The parameters are interrelated. Based on the analytical solution, Raghunathan (1995a) has given recommended values for these parameters, which are listed in Table 1-1. To achieve maximum efficiency and wide operating range, optimum values of these parameters are required. [16]

Table 1-10: Parameters of Wells Turbine

Parameters	Analytical Description	Remarks
Solidity(σ)	$zc/\pi R_t$	Efficiency reduces for $\sigma > 0.5$
Hub-to-tip ratio (h)	R_h/R_t	Recommended value for h~0.6
Aspect Ratio (AR)	b/c	AR = 0.5 is recommended for turbine design
Tip clearance (τ_t)	$\%\ of\ c$	τ_t > 2% of c is recommended for significant advantage

Solidity is a method of calculating the blockage of airflow within the Wells turbine and measuring the mutual interaction between the blades. Blades become too close together as solidity increases. As a result, blades interact with the boundary layer at the hub, causing boundary layer separation on the surface of the hub as well as on the blade surface near the hub. This creates end wall losses in the hub region. The effect of the hub-to-tip ratio has been well studied, and the results show that as the hub-to-tip ratio increases, efficiency decreases. [16]

1.7.1.3.3 Types of Wells Turbine

- **Wells turbine with guide vanes**

The turbine (turbine diameter of 1.7m, 2 tandem turbines, NACA0021, 8 blades per rotor, rated output of 30kW × 2) was adopted for the project "Mighty Whale" organized by JMSTEC, Japan (Figure1-27). This turbine has been also connected with the Azores Pico Plant supported by EU. [17]

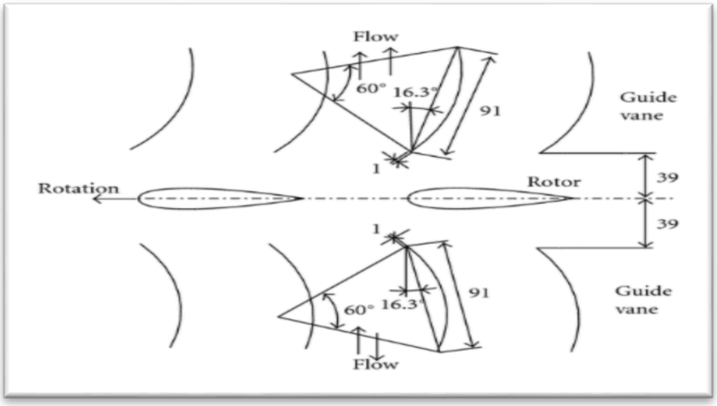


Figure 1-25: Wells turbine with guide vanes.

- **Wells turbine with self-pitch-controlled blades**

A turbine blade is set on the hub by a pivot located near the leading edge that enables it to oscillate between two prescribed setting angles. As an airfoil set at a certain angle of incidence generates the pitching moment *M* about a pivot, the turbine blades can oscillate between two setting angles by themselves according to the flow direction (Figure 1-28). [17]

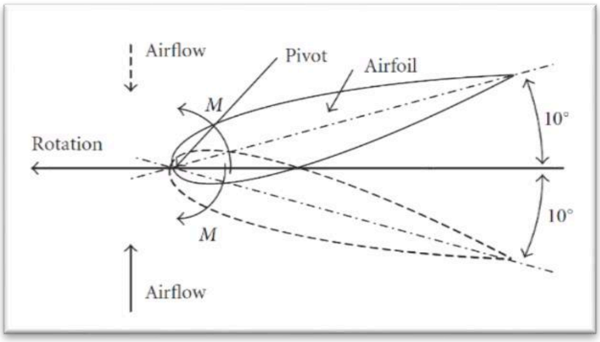


Figure 1-26: Turbine using self-pitch-controlled blades (TSCB).

- **Biplane Wells turbine with guide vanes**

This turbine (Figure 1-29) is installed in OWC plant (turbine diameter of 1.2 m, rated output of 75kW), Islay, U.K, where the guide vanes are not used for the turbine. [17]

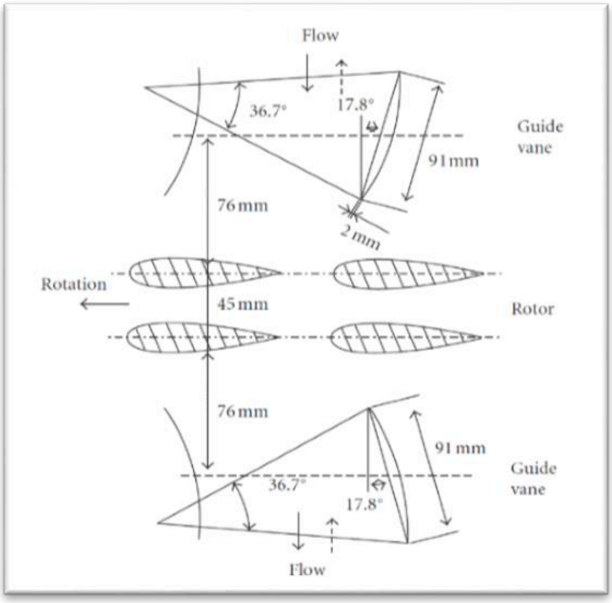


Figure 1-27: Biplane Wells turbine with guide vanes (BWTGV).

- **Contra rotating Wells turbine**

The contra rotating wells turbine (Figure 1-16) was installed in the LIMPET, Islay, U.K, which is the world's first commercial wave power station (capacity of 500kW, turbine diameter of 2.6 m, 2 turbines, NACA0012, 7 blades per rotor). However, detailed information of the turbine characteristics has not been clarified. [17]

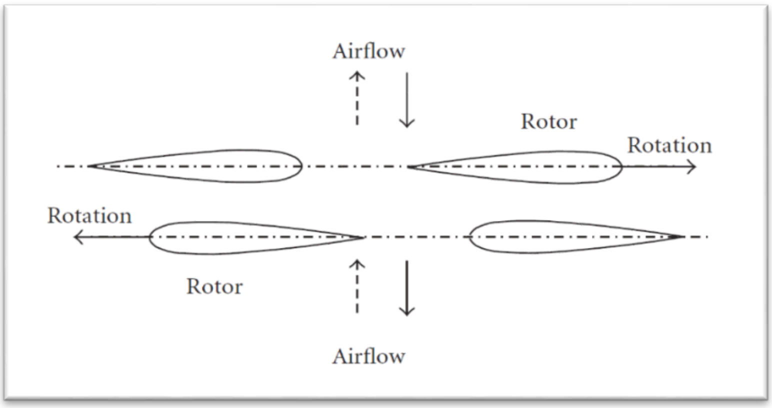


Figure 1-28: Contra rotating Wells turbine.

Chapter two

Wave energy systems

Chapter Two

2. WAVE ENERGY SYSTEWMS

2.1 POINT ABSORBERS

A point absorber is a floating structure which absorbs energy from all directions through its movements at/near the water surface. It converts the motion of the buoyant top relative to the base into electrical power. The power take-off system may take a number of forms, depending on the configuration of displacers/reactors.

Point absorbers extract energy through the relative motion between a body that moves in response to wave forcing and fixed or immobile structures. The moving body may be on the surface or submerged, and the 'fixed' body may be the seabed or another structure less affected by wave action. Their principal dimension is small relative to the length of waves they are absorbing energy from. Electricity may be produced using a linear or rotary generator, or a fluid may be pumped using mechanical force and motion directly.

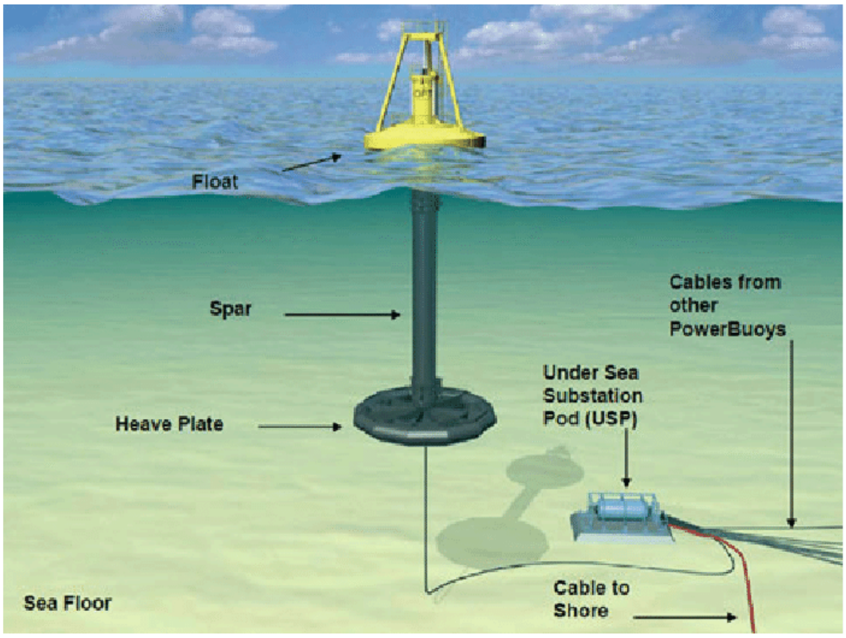


Figure 2-1: Point absorbers.

Point absorber wave energy converters are floating structures that have a small horizontal dimension compared with their vertical dimension and utilize the wave action at a single point. Most designs for point absorbers resemble a run-of-the-mill buoy, at least from the surface. In the typical point absorber design one end of the absorber is fixed (or at least fixed relative to the water's surface) while the other end moves in a vertical motion as the wave crests and troughs lift and lower the device. The resulting reciprocating action is used to pump a fluid or drive a linear generator, which in turn can provide usable power. Referencing our six degrees of freedom above, this device takes advantage of the heaving motion from the up-and-down of ocean waves. Point absorbers are one of the most prevalent design archetypes in the marine energy sector today. [18]

2.2 OVERTOPPIN/TERMINATOR DEVICE

An oscillating water column is a partially submerged, hollow structure. It is open to the sea below the water line, enclosing a column of air on top of a column of water. Waves cause the water column to rise and fall, which in turn compresses and decompresses the air column. This trapped air is allowed to flow to and from the atmosphere via a turbine, which usually has the ability to rotate regardless of the direction of the airflow. The rotation of the turbine is used to generate electricity.

Overtopping terminators, also referred to just as terminators, are devices that take advantage of wave energy to generate electricity. Scientists have been doing research since the 1990s to develop overtopping devices, but not until recently has significant progress been made (Bevilacqua & Zanuttigh, 2011). The overtopping terminator is a large device that is categorized as a wave capturer. This means that instead of using a wave's kinetic energy to generate power like other wave energy devices, the terminator captures waves and takes advantage of their potential energy (Katofsky, 2008). In fact, the terminator got its name because of the way it absorbs or "terminates" all of a wave's power. (Bedard et al, 2010).

Plans have been proposed to install overtopping terminators both on and offshore. However, after Demark made great improvements with the offshore model it became the primary method of development and the onshore method's progress diminished. Now overtopping terminators are described as large, floating reservoirs with ramps and reflectors extending off the end and turbines located at the bottom of the reservoir. The terminators are up to 390 meters wide and can hold between 1,500 and 14,000 cubic meters of water.

The average cost to build and install one of these devices is a steep $10 to $12 million but its high efficiency makes it worth the cost in the long run (US Dept. of Energy, 2009).

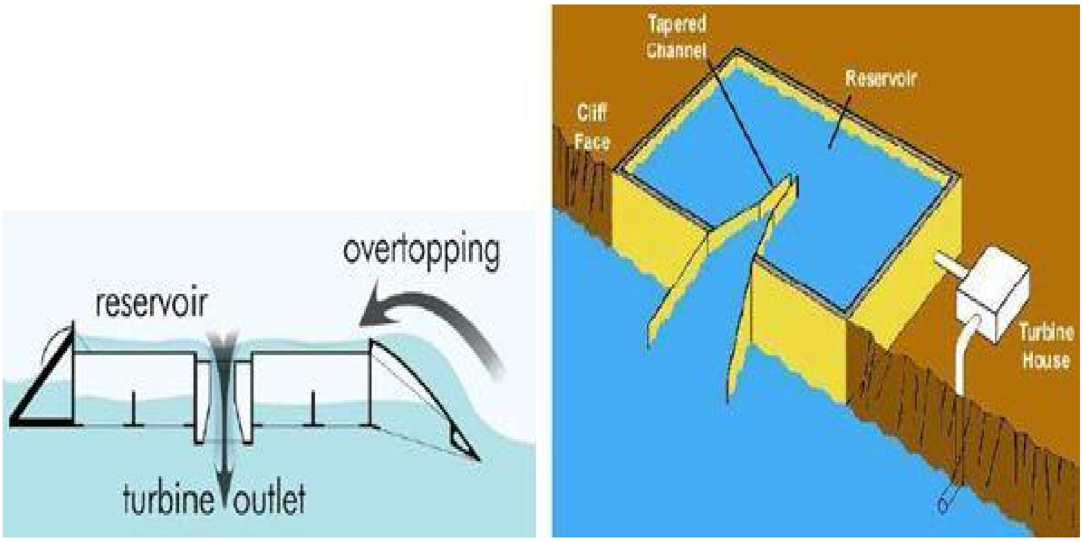


Figure 2-2: Overtopping/Terminator Device.

When waves first approach an overtopping terminator, they bump into its reflectors. These reflectors are attached to the main body of the floating device and are angled outward in order to direct as much wave energy up to the device as possible.

The reflectors gradually rise in height and compress in width, leading the water all the way up to the reservoir. The overtopping device receives the incoming waves at their maximum heights due to the placement of the ramp, which is shallow enough to cause the incoming waves crash over into the reservoir – hence the name "overtopping" terminator. The reservoir is located at a height slightly above sea level to increase the amount of potential energy it contains (Czech, 2012).

Once the water is captured in the reservoir, it is released back into the ocean via a turbine outlet located near the middle of the device. The turbines are coupled to generators to produce energy (EPRI, 2007).

Wave Dragon devices are the most widely known overtopping terminators and several projects are located in waters off the coast of Wales, Portugal, and Denmark (*Wave Dragon*, 2005). Full sized units are constructed with concrete and steel, weigh 22,000 tonnes, and cover a span of 260 meters.

The Wave Dragon is located in water more than 25 meters deep in order to take advantage of ocean waves with the highest amount of energy. A pressurized system of air chambers allows the Wave Dragon's height to be adjustable which also increases the amount of energy the device is capable of capturing with their 16-20 turbines that spin as water is released from the reservoir. Depending on wave activity, each unit has a rated power of 4-10 MW. The prototype that was launched off the coast of Denmark in 2003 has generated more than 20,000 hours of electrical power and continues to contribute today. [19]

2.3 ROTATING MASS

Rotating mass wave energy converters are generally surface riders that use an internal weight rotating (gyroscope or eccentric weight) about a fixed point to drive a rotational alternator. The rocking motion of ocean waves cause the hull's center of buoyancy and center of gravity to shift, and the rotating mass thus rotates about its axis to find its new center point as the vessel's trim and pitch fluctuate. Since waves keep the device constantly rolling and swaying, the mass is constantly rotating trying to reach equilibrium while also generating power.

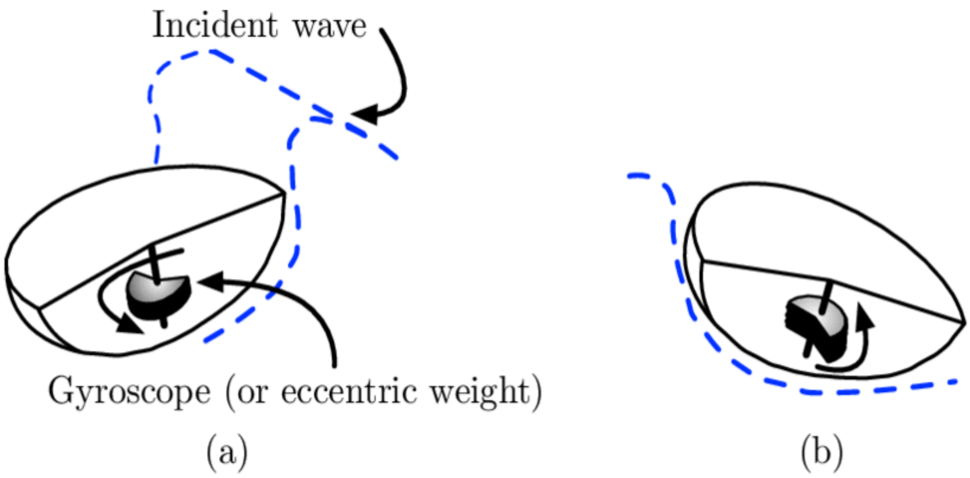


Figure 2-3: Schematic view of Rotating Mass Converter.

The rotating mass creates power through an electrical generator. An example of this device is the Penguin by Wello. [20]

Figure 2-4: Wello's Penguin Device.

2.4 OSCILLATING WAVE SURGE

Oscillating wave surge converters (OWSCs) are a class of wave power technology that exploits the enhanced horizontal fluid particle movement of waves in the nearshore coastal zone with water depths of 10–20 m. OWSCs predominantly oscillate horizontally in surge as opposed to the majority of wave devices, which oscillate vertically in heave and usually are deployed in deeper water. The OWSC is designed to couple strongly with the horizontal particle motion, permitting large amplitudes of motion of the working surface whilst minimizing energy losses in associated water particle motions.

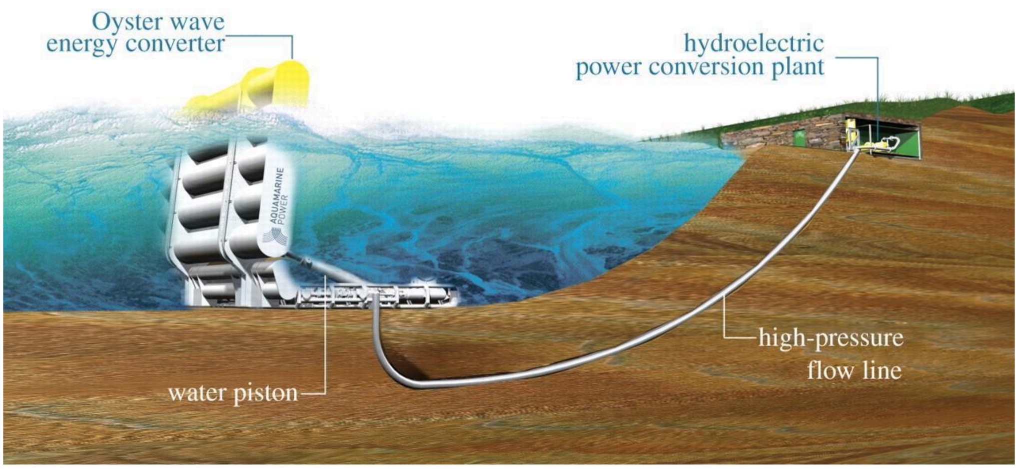


Figure 2-5: Oscillating Wave Surge Converter.

The OWSC consists of a paddle rotating about a horizontal axis above the water surface and perpendicular to the direction of wave propagation. The paddle hangs at the mouth of a gully, effectively forming a ‘water column’ between the paddle and gully back wall. The concept of the OWSC evolved from the analysis of shoreline OWC’s. Fundamentally, an OWC consists of a box with an underwater opening so that a water column in the box rises and falls in response to waves. This movement of the water surface causes air to be driven through an air-turbine. Because a water surface must remain approximately horizontal, to change the air volume in the box the water surface must move orthogonally to this, i.e., vertically.

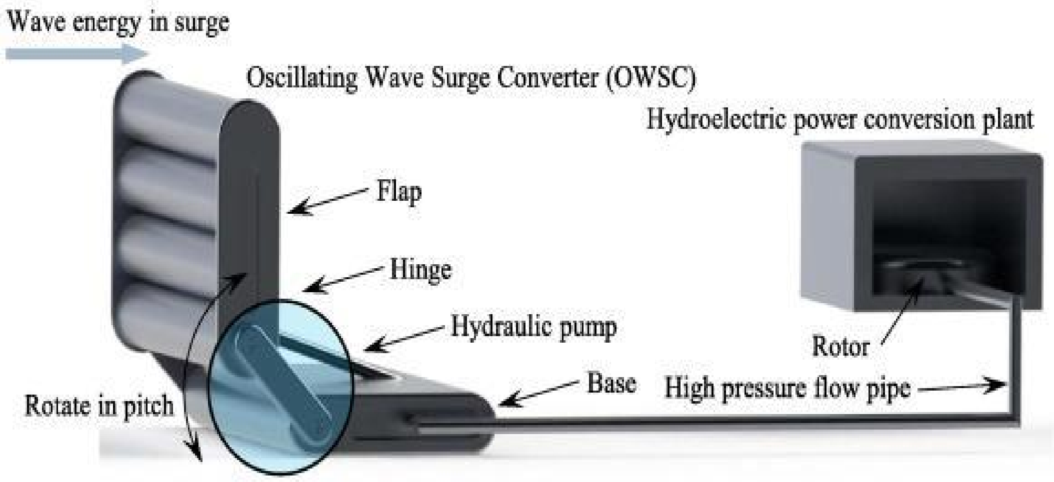


Figure 2-6: Working Principle.

The OWSC is similar to the Japanese ‘Pendulor’ system; This device rests on the seafloor, and resembles a paddle attached to a pivoted joint. As waves pass overhead, the paddle moves with water particles to capture the wave's energy.

However, the OWSC uses resonance of the water column rather than harbor resonance as its operating principle. A limited study of geometric parameters using a two-dimensional wave-tank model has been performed. Results from these experiments have shown that the ‘water column’ has an effect on the paddle dynamics and OWSC performance, with the OWSC having a higher power capture than both a shoreline oscillating water column (OWC) and Pendulor in shallow water.

The potential for the OWSC in the shoreline and near-shore regions is also discussed, with implications for construction costs and the price for electricity generated by the OWSC. Potential control strategies for the OWSC are also discussed, together with their likely effect on operation and performance. [21]

2.5 SUBMERGED PRESSURE DIFFERNTIAL

Submerged or semi-submerged devices that use differences in pressure to generate electricity. Bulge wave devices, for example, are typically water-filled rubber tubes that use pressure variations created by waves to drive a turbine. Similarly, submerged point absorbers use the pressure difference between wave crests and troughs to drive a turbine. This sits on the seafloor, typically near shore. The waves passing overhead cause the water level above the device to rise and fall, creating a pressure differential which drives the device. The Archimedes wave swing[4] is one such device. It uses the oscillating hydrodynamic pressure caused by passing waves. Pressure Differential devices rely on oscillating hydrodynamic pressure caused by passing waves. For submerged devices what we have is that waves pass over the device, creating a temporary vertical force on the body. Once the wave has passed, the reduced pressure differential causes the body to return down to its starting position. [22]

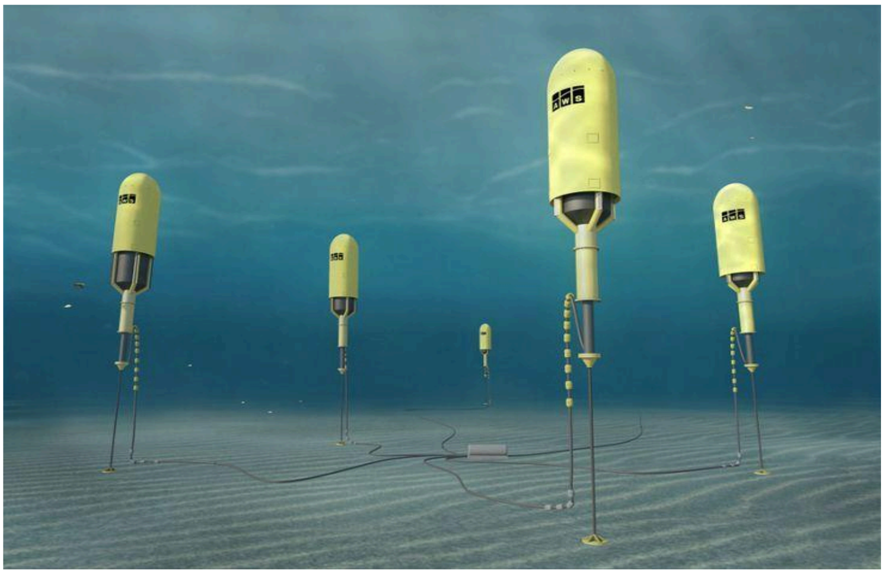


Figure 2-7: Submerged Pressure Differential.

2.6 OSCILLATING WATER COLUMN

Oscillating water columns (OWCs) are a type of wave energy converter that harness energy from the oscillation of the seawater inside a chamber or hollow caused by the action of waves. OWCs have shown promise as a renewable energy source with low environmental impact. Because of this, multiple companies have been working to design increasingly efficient OWC models. OWC are devices with a semi-submerged chamber or hollow open to the sea below, keeping a trapped air pocket above a water column. Waves force the column to act like a piston, moving up and down, forcing the air out of the chamber and back into it. This continuous movement forces a bidirectional stream of high-velocity air, which is channeled through a power take-off (PTO).

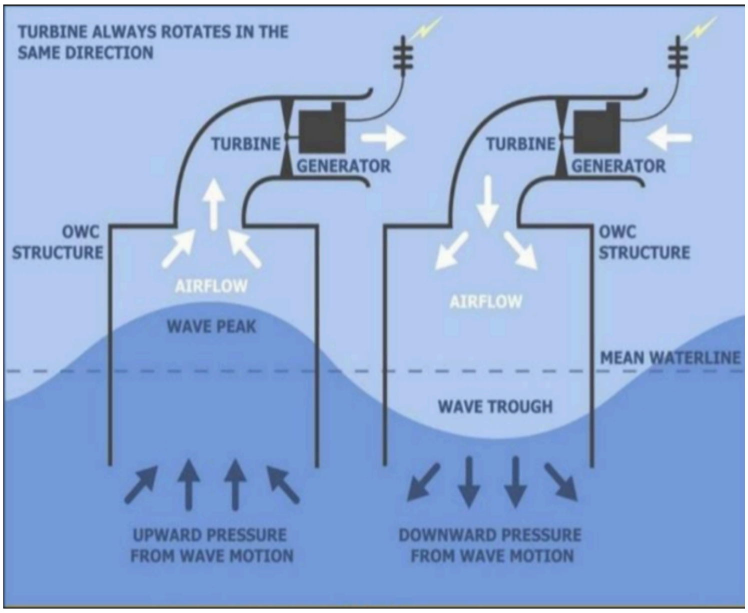


Figure 2-8: Oscillating Water Column Converter.

The PTO system converts the airflow into energy. In models that convert airflow to electricity, the PTO system consists of a bidirectional turbine. This means that the turbine always spins the same direction regardless of the direction of airflow, allowing for energy to be continuously generated. Both the collecting chamber and PTO systems will be explained further under "Basic OWC Components. [23]

2.7 ATTENUATOR

Attenuators are situated parallel to the force and direction of a wave. They are held in place by mooring on the seabed. The motion of the device from the crest and trough of the wave exerts force on a turbine that then feeds energy into the grid.

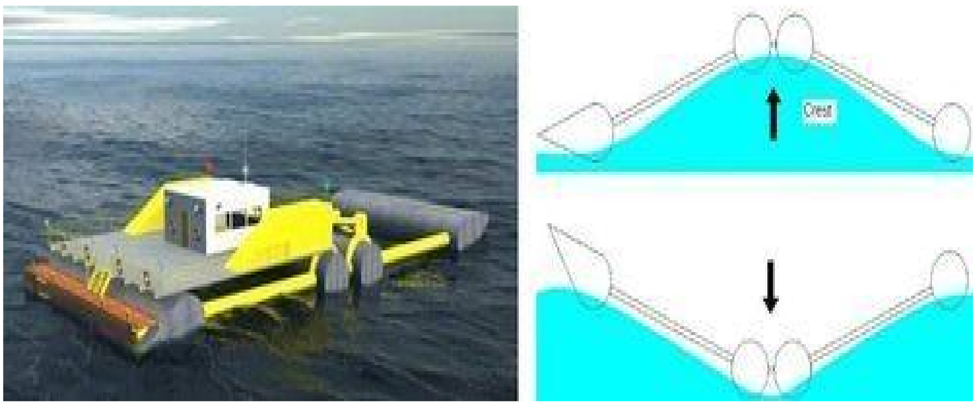


Figure 2-9: DEXA wave energy converter and working principle.

The "DEXA", developed and patented by DEXA Wave Energy ApS , is an illustrative example of a wave attenuator. The device consists of two hinged catamarans that pivot relative to the other. The resulting oscillatory flux at the hinge, is harnessed by means of a water-based low pressure power transmission that restrains angular oscillations. Flux generation is optimized by placing the floaters of each catamaran half a wavelength apart. A scaled prototype (dimensions 44x16.2m) placed in the Danish part of the North Sea should generate 160 kW. Full-scale models are thought to be able to generate up to 250 kW. However, the DEXA development was terminated in 2012. [24]

Chapter three

Mathematical Formulation

Chapter Three

3. MATHEMATICAL FORMULATION

3.1 MODEL STATEMENT

In this section, the interaction of the waves with the OWC chamber construction is modelled. To analyse the dynamic performance of the airflow in the capture chamber, first characterise the wave propagation behaviour. Firstly, a model of wave surface dynamics is provided. The model is then linked to the pressure change in the OWC chamber, particularly the pressure drop in the turbine blades, illustrating the relation between the waves and the airflow through them. Finally, the mechanical characteristics are considered to obtain the resulting rotational speed and torque to be applied to the induction generator.

3.1.1 Wave's Surface Dynamics

According to the Airy linear theory,

$y(t) = a \cdot \sin sin\,(\omega \cdot t) \; = a \cdot \sin sin\,(2\pi f \cdot t)\,,$

3.1

Where $c = \lambda f$, so that,

$y(t) = a \cdot \sin sin \left(\frac{2\pi}{\lambda} \cdot ct\right).$

3.2

This expression represents the temporal variation for wind wave of amplitude (a), wavelength (λ), and propagation speed (c), as a macroscopic depiction of the oscillating behaviour of water particles at a single site. In order to transfer the oscillation movement to any point on the surface, an additional variable corresponding to the spatial dimension in the wave's front direction must now be considered:

$y(x, t) = a \cdot \sin sin\,(\frac{2\pi}{\lambda}\,(ct \; - \; x))\,.$

3.3

Then, take into consideration that the wave number is defined as

$k = \frac{2\pi}{\lambda},$

3.4

So that (3.3) may be written as,

$y(x, t) = \; \frac{H}{2} \bullet \; \sin sin\,(\omega t \; - \; kx),$

3.5

Where H is the wave height.

This expression represents the surface dynamics of a monochromatic linear wave as a function of the wave parameters.

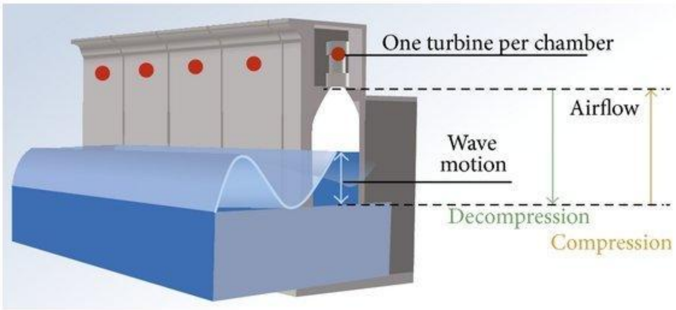


Figure3-1: On-shore MOWC system schematic.

Figure3-2: Turbo-generator Module.

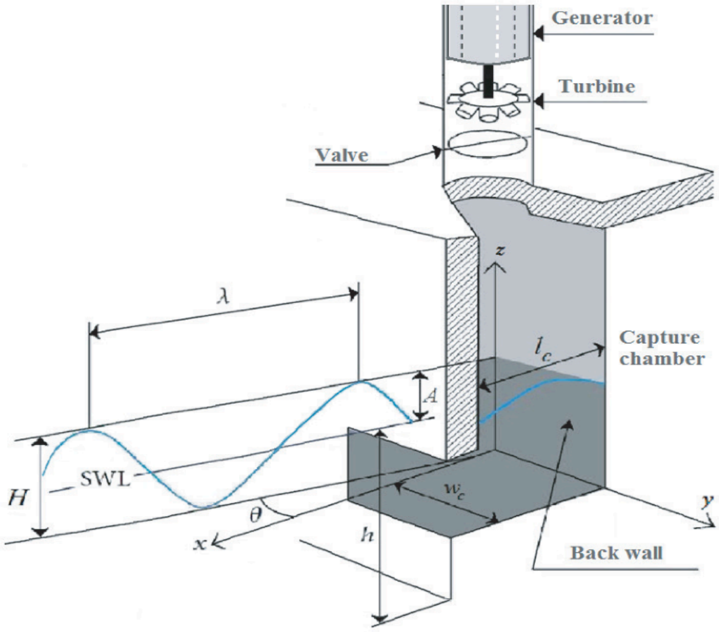


Figure3-3: Sketch of an Oscillating Water Column (OWC) system and the sea wave.

3.1.2 Capture Chamber Model

The final goal is to get the torque and angular speed of the turbine, which will be used as inputs to the turbo generator. As will be demonstrated, these variables are indirectly related to the axial speed of the airflow through the turbine's blades. The air volume in the OWC chamber can be calculated using the water volume:

$V(t) = V_c - V_\omega(t),$

3.6

Where V_c and V_ω represent the capture chamber and water volumes, respectively.

Then, by integrating the orthogonal variation of the water surface along the chamber's length:

$V(t) = V_c - \iint y(x, t)dA.$

3.7

Because of the OWC chamber's geometry,

$dA = w \cdot dx,$

3.8

Where w is the width of the chamber. Therefore, one has

$V(t) = V_c + \frac{wH}{k} \sin sin \frac{kl}{2} \sin sin\, \omega t,$

3.9

Where l is the length of the chamber. It is now possible to obtain the expression for the instantaneous airflow:

$Q_a(t) = wHc\cdot sin\frac{kl}{2}\cos cos\ \omega t$.

3.10

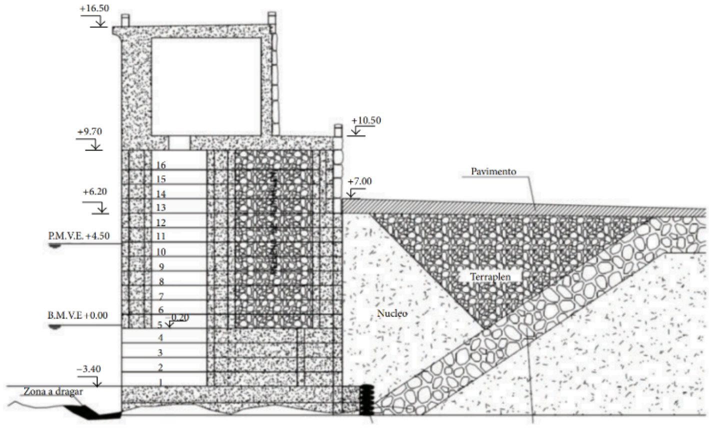


Figure3-4: Capture chamber construction plan of Mutriku wave plant.

By using this expression and the topology of the OWC chamber in Mutriku, where the airflow is conducted through a second axisymmetric duct where the turbo-generator module is located (Figure 3-4), the axial airflow speed ($V = \frac{Q}{A}$) can be calculated:

$v_t = \frac{8awc}{\pi D^2} \bullet \sin sin\ \frac{\pi l}{cT}\cos cos\ \frac{2\pi}{T}t,$

3.11

Where D is the diameter of the duct.

3.1.3 Analytical mathematical model on Wells turbine performance:

This section outlines the first law analysis method utilised to measure in this study. In addition, an analytical mathematical model was used to study the efficiency estimations for the Wells turbine under sinusoidal-flow conditions. The net torque that drives the Wells turbine is the sum of all torques applied to the turbine, as follows:

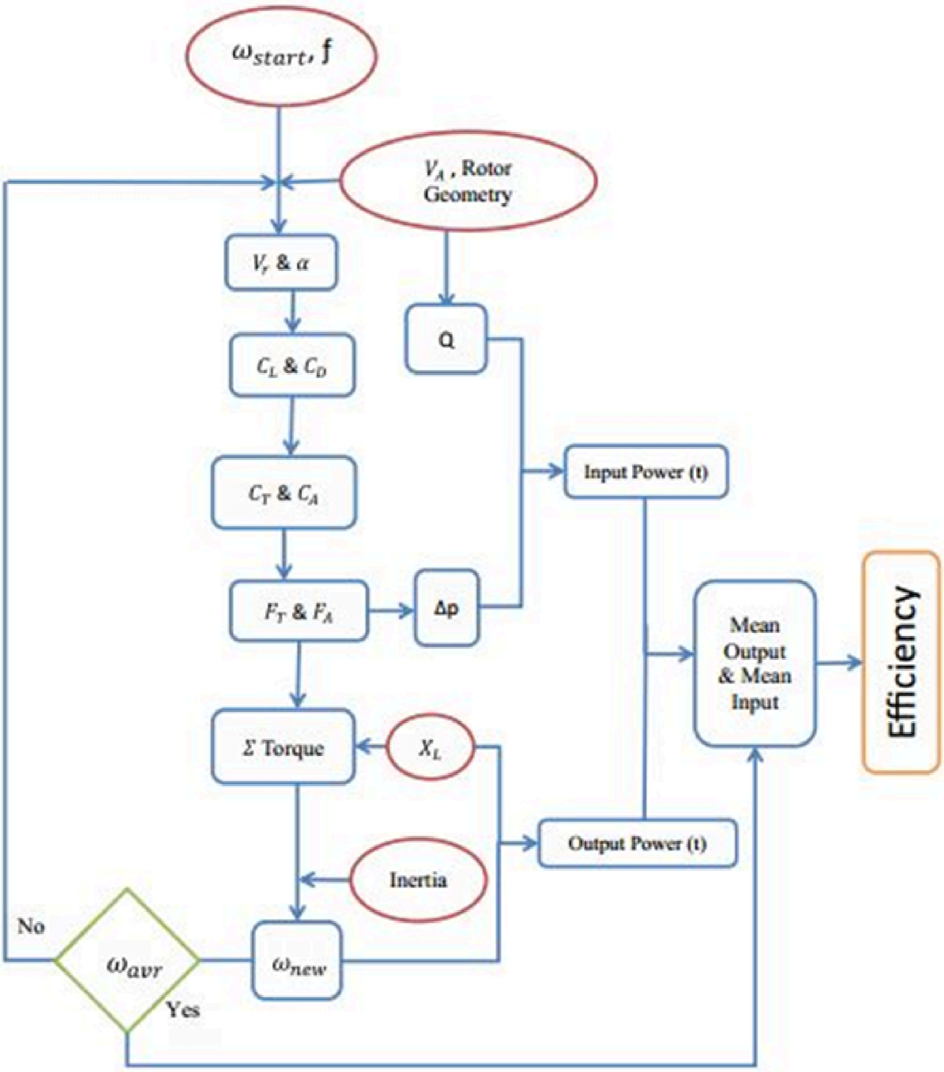


Figure3-5: Flow chart of implementing analytical mathematical model of wells turbine performance.

$$\sum Torque = T_{aerodynamic} - T_{load} - T_{loss}, \quad 3.12$$

$$\sum Torque = \frac{1}{2}\rho(V_a^2 + (\omega R_m)^2)AR_m C_T - T_L - T_{loss},$$

3.13

Where T_L is the load torque.

Be using the angular moment equation of motion along the turbine axis, we obtain:

$$I\frac{d\omega}{dt} = \sum Torque,$$

3.14

Where I is the rotor mass moment of inertia and ω is the rotor's angular velocity as a function of time.

By neglecting the torque losses and substituting equation (3.13) for equation (3.14), we obtain:

$$I\frac{d\omega}{dt} = \frac{1}{2}\rho(V_a^2 + \left(\omega R_m\right)^2)zcbR_m C_T - T_L$$

3.15

The load torque can be expressed non-dimensionally as follows:

$$X_L = \frac{T_L}{\rho\pi R_M^3 V_a^2}$$

3.16

As a result, the equations of motion for the rotor are as follows:

$$I\frac{d\omega}{dt} = \frac{1}{2}\rho(V_a^2 + \left(\omega R_m\right)^2)zcbR_m C_T - X_L\rho\pi R_M^3 V_a^2$$

3.17

$$\frac{d\omega}{dt} = \frac{\frac{1}{2}\rho(V_a^2+\left(\omega R_m\right)^2)zcbR_m C_T - X_L\rho\pi R_M^3 V_a^2}{I}$$

3.18

$$\int d\omega = \int \frac{(\frac{1}{2}\rho(V_a^2+\left(\omega R_m\right)^2)zcbR_m C_T - X_L\rho\pi R_M^3 V_a^2)}{I}\, dt \qquad 3.19$$

$$\omega_2 - \omega_1 = \frac{\frac{1}{2}\rho(V_a^2+\left(\omega R_m\right)^2)zcbR_m C_T - X_L\rho\pi R_M^3 V_a^2}{I}\, t_2 - t_1 \qquad 3.20$$

For the first law of thermodynamics, the lift and drag coefficients CL and CD are computed from the post processing software. The torque coefficient is then expressed as:

$$C_T = (C_L \sin sin \propto\ - C_D \cos cos\ \propto\ )$$

3.21

The flow coefficient f relating the rotor's tangential and axial velocities is defined as:

$$\emptyset = \frac{V_a}{\omega \cdot R_m}$$

3.22

Where alpha (α) is the angle of attack, which is defined as the angle between a body's reference line (chord line) and relative wind.

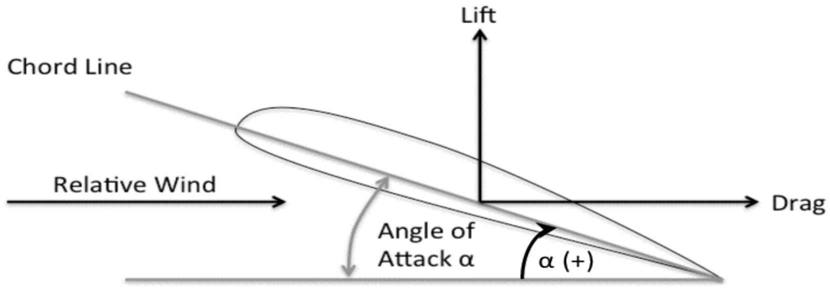


Figure 3-6: Airfoil angle of attack illustration.

And ∝ is equal to:

$$\propto \; = \; tan^{-1} \frac{V_a}{\omega \cdot R_m}$$

3.23

As a result, the output Power can be calculated by using the equation below:

$$Output\ Power \; = X_L \rho \pi R_M^3 V_a^2 \bullet \omega_{avr} \qquad 3.24$$

Where X_L is the non=dimenesional loading torque.

And the equation for input power is:

$$Input\ power \; = \frac{1}{T} \int_0^T \Delta p \cdot Q dt \qquad 3.25$$

Where Q is the volume flow rate from the rotor area to the turbine and is provided by:

$$Q \; = V_A \bullet A_r$$

3.26

The efficieny in the first law of thermodynamics (η_F)

$$\eta_F \; = \; mean\ value\ of\ \frac{Output\ power}{Input\ power} \; = \frac{\frac{1}{T} \int_0^T T_L \omega(t) dt}{\frac{1}{T} \int_0^T \Delta p \cdot Q dt} \qquad 3.27$$

3.1.4 Turbine Model

The pressure drop (dp) can be calculated using the preceding data and turbine parameters

$$dp \; = C_a \frac{\rho b l_1 n}{2} \frac{1}{a_1} \left(v_t^2 + \left(r \cdot \omega_t \right)^2 \right), \qquad 3.28$$

Where ρ is the air density (kg/m^3), b is the blade's height (m), l_1 is the length of blade's chords (m), n is the number of blades, a_1 is the blade's section area (m^2), r is the turbine's mean diameter (m), and ω_t is the turbine's angular speed (rad/s).

This expression is obtained by solving Bernoulli's equation throughout the disc, keeping in mind that under steady-state conditions, the total energy of the flow remains constant as long as no work is done on the fluid. As seen, the pressure drop is also affected by the rotational speed, which is proportional to the torque applied to the turbine. This interaction can be modelled by applying Newton's Second Law to rotational motion:

$$H\dot{\omega}_t + F\omega_t + T_e = T_t, \quad 3.29$$

Where H is the inertia coefficient, F is the friction coefficient, ω_t is the rotational speed, T_t is the turbine torque, and T_e is the electrical torque (applied by the inductor generator). Additionally, the turbine's torque follows the expression:

$$T_t = C_t Kr\left(v_t^2 + \left(r\cdot\omega_t\right)^2\right). \quad 3.30$$

As shown by the previous three equations, there is a feedback relation between the behaviour of the turbogenerator and the pressure drop through the turbine blades, because the pressure drop through the turbine is rotational speed, but the generated pressure drop also influences the rotational speed via the applied torque.

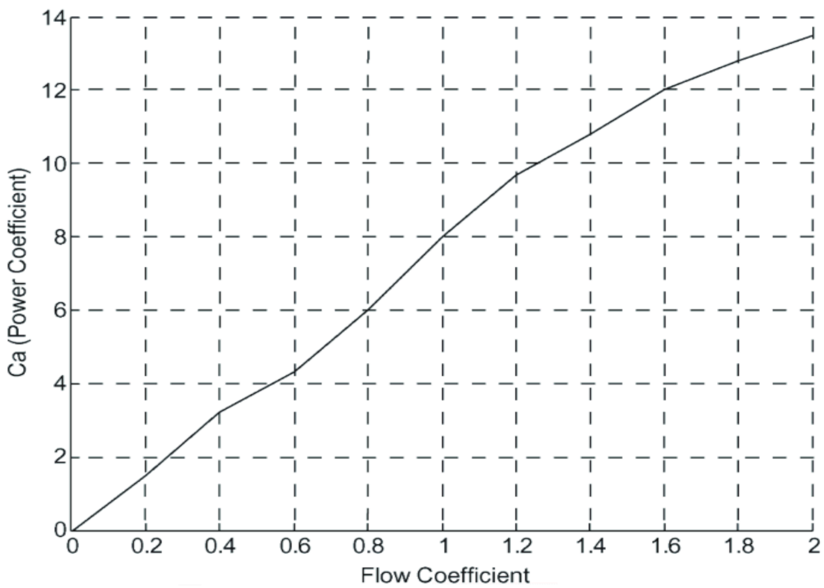


Figure 3-7: Power coefficient versus flow coefficient.

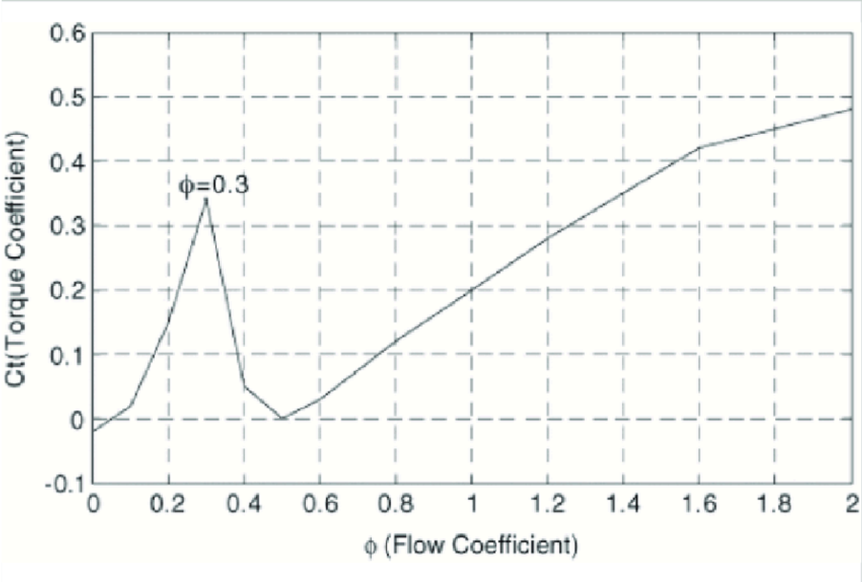


Figure 3-8: Torque coefficient versus flow coefficient.

In order to answer the aforementioned expressions, the power coefficient (C_a) and torque coefficient (C_t) must be computed in relation to the flow coefficient ($\emptyset$) using the turbine's characteristic curves (Figures 3-7 and 3-8). The flow coefficient can then be determined as follows:

$$\emptyset = \frac{v_t}{r\cdot\omega_t}.$$

3.31

As a result, and recalling (3.28), the pressure drop through the turbine can be expressed in terms of wave features, ocean structure characteristics, and turbo generator behaviour as follows, with $f(.)$ being a function matching the C_a and values according to the relevant turbine characteristic

s:

$$dp = f\left(\frac{v_t}{r\cdot\omega_t}\right) \bullet \frac{\rho b l_1 n}{2} \bullet \frac{1}{a_1}\left(\left(\frac{8awc}{\pi D^2} \bullet \sin sin \frac{\pi l}{cT}\right)^2 \frac{2\pi}{T} t + \left(r\cdot\omega_t\right)^2\right).$$

3.32

Table 3-1: Parameters of the wells turbine and OEC chamber.

Air density (ρ)	1.19 kg/m^3
Blade height (b)	0.03 m
Length of blades chord (l_1)	0.165 m

Number of blades (n)	5
Blade's section area (a_1)	0.004 m^2
Turbine's mean diameter (r)	0.375 m
Chamber width (w)	4.5 m
Chamber length (l)	4.3 m

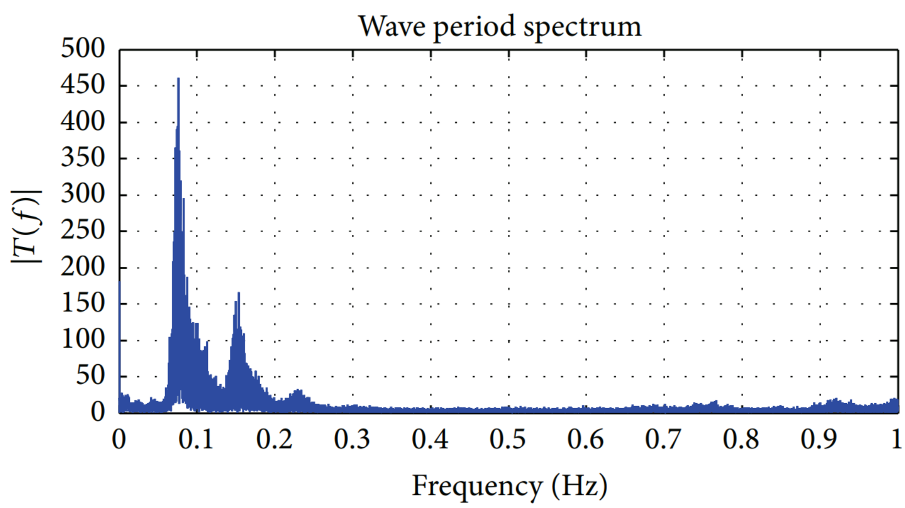


Figure 3-9: frequency analysis of the waves.

3.2 OSCILLATING WATER COLUMN FORCE ANALYSIS

3.2.1 Compression Stage:

The operation of W-T is classified into two stages , the first stage is the compression stage , in which the water level rises inside the housing .

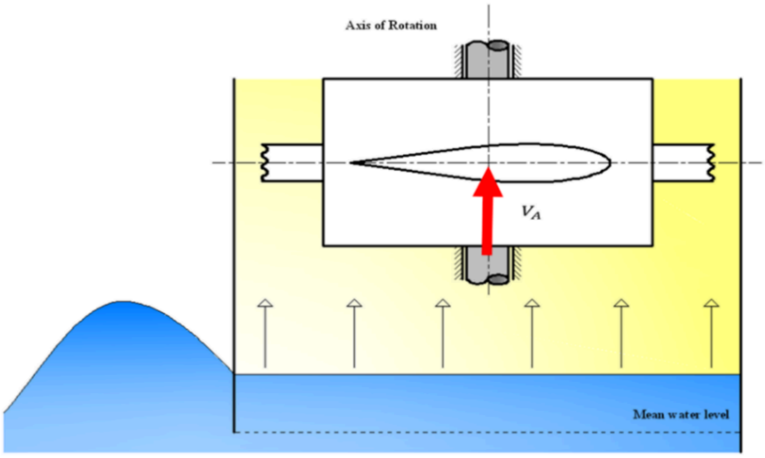


Figure 3-10: Airfoil with flow moving from down to up.

When water level rises inside the duct, in (Figure 3-10)the flow is movig from downward to upward that will cause the hub to rotate that will generate angular velocity as shown in (Figure3-11).

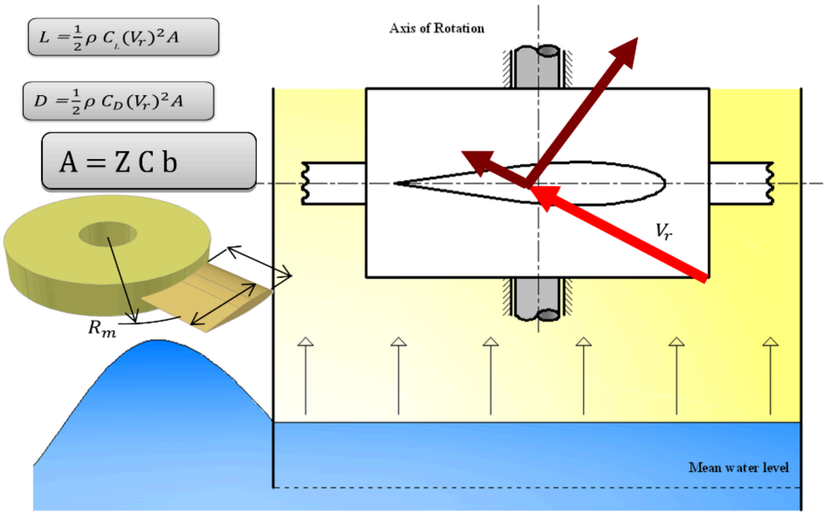


Figure 3-11: Airfoil with flow moving at an angle.

The resultant aerodynamic force F_R due to lift and drag force as shown in (Figure 3-12).

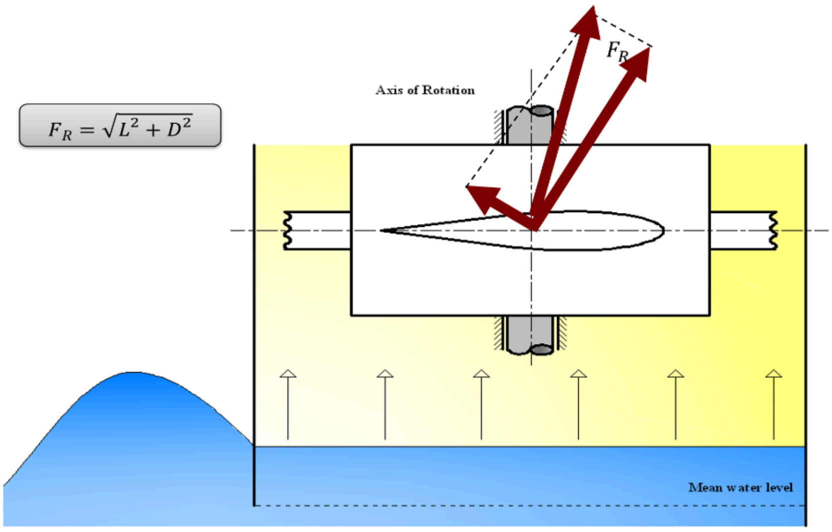


Figure 3-12: Airfoil resultant force analysis.

This force can be decomposed in two components into axial and tangential directions in terms of lift and drag components as shown in (Figure 3-12).

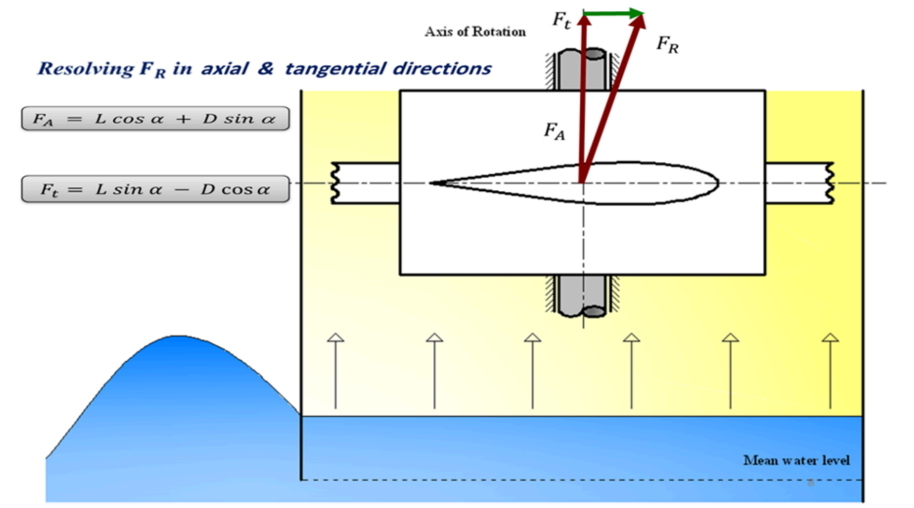


Figure 3-13: Airfoil resolving resultant force and tangential force.

Where F_A is the axial force and F_t is the tangential force.

3.2.2 Suction stroke

Second , the suction stage in which the water level drops , sucking air into the duct .

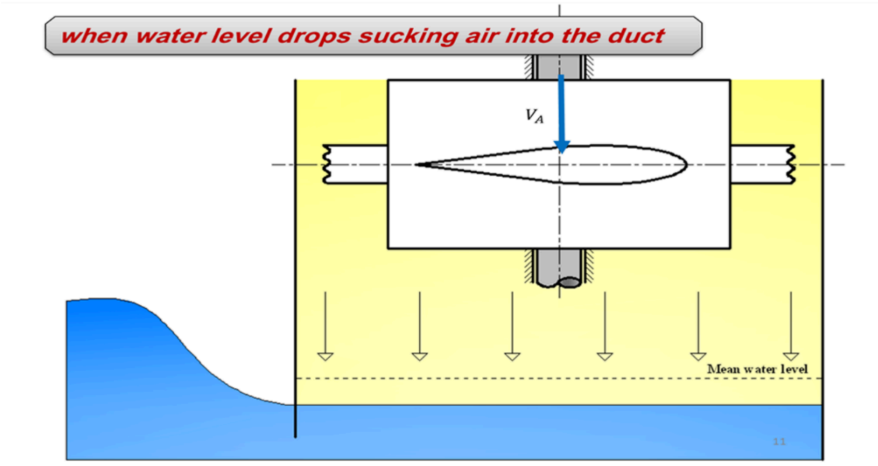


Figure 3-14: Airfoil in suction stroke.

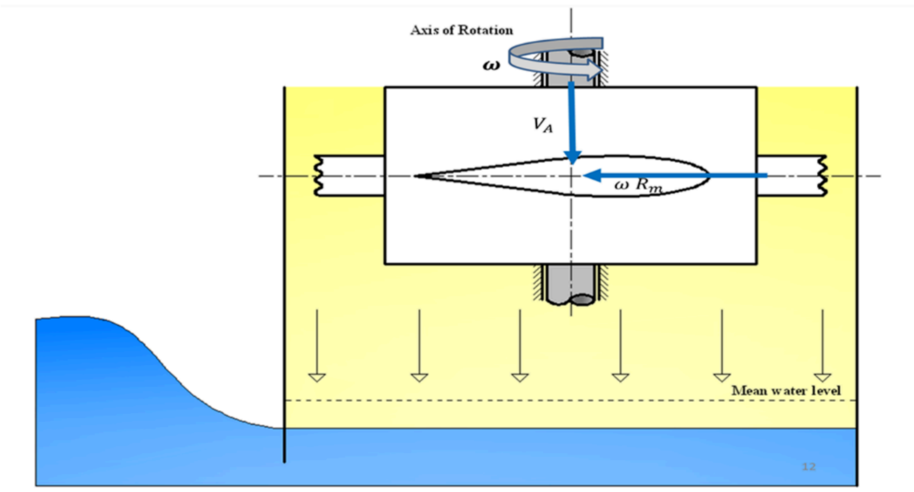


Figure 3-15: Airfoil with flow generating rotational motion.

In (Figure 3-14) The flow is movig from upward to downward that will cause the hub to rotate that will generate angular velocity as shown in (Figure 3-15).

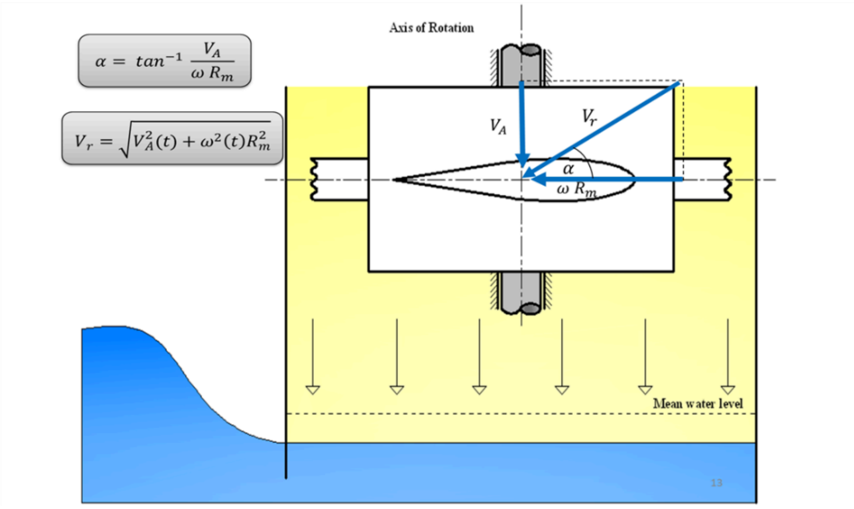


Figure 3-16: Airfoil with V_A and V_R analysis.

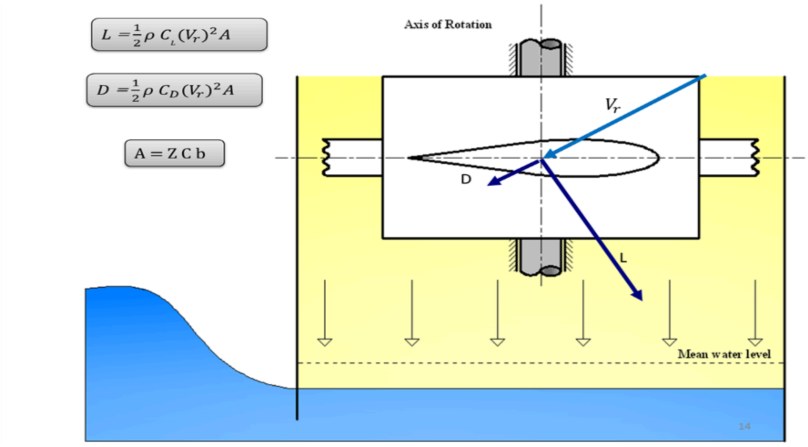


Figure 3-17: Air foil with V_r extended to D.

The resultant aerodynamic force F_R due to lift and drag force as shown in (Figure 3-18).

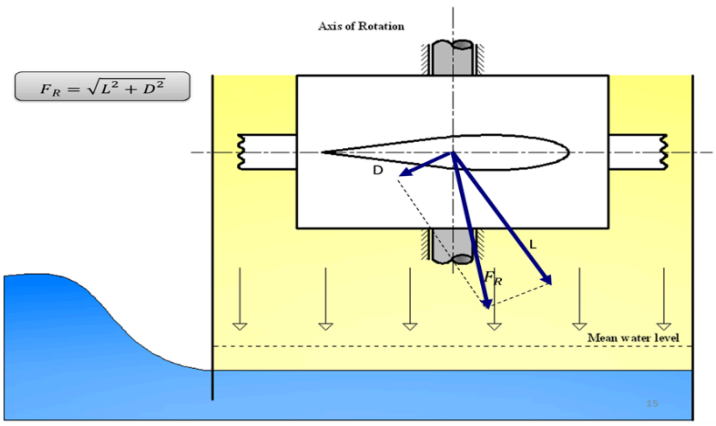


Figure 3-18: Airfoil with resultant force F_R.

This force can be decomposed in two components into axial and tangential directions in terms of lift and drag components as shown in (Figure 3-19).

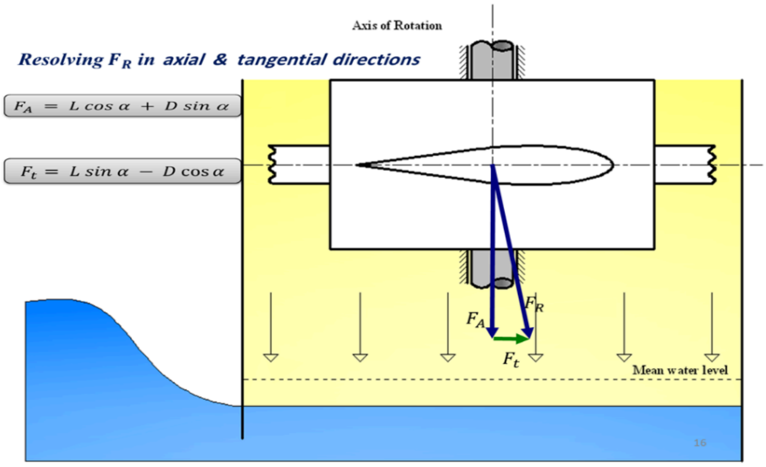


Figure 3-19: Airfoil with F_R in axial and tangential directions.

3.2.3 Comparison between compression and suction

During the two stages, the tangential force remains in the same direction as shown in (Figure 3-20), while the axial force changes its direction, and the tangential force remains in the same direction for both positive and negative values of angle of attack, as shown in (Figure 3-21).

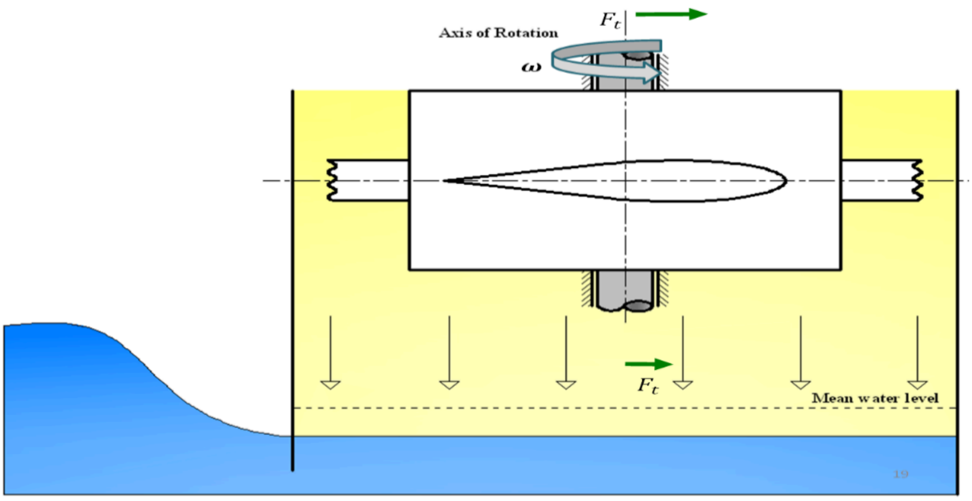


Figure 3-20: Tangential force effect on axis of rotation.

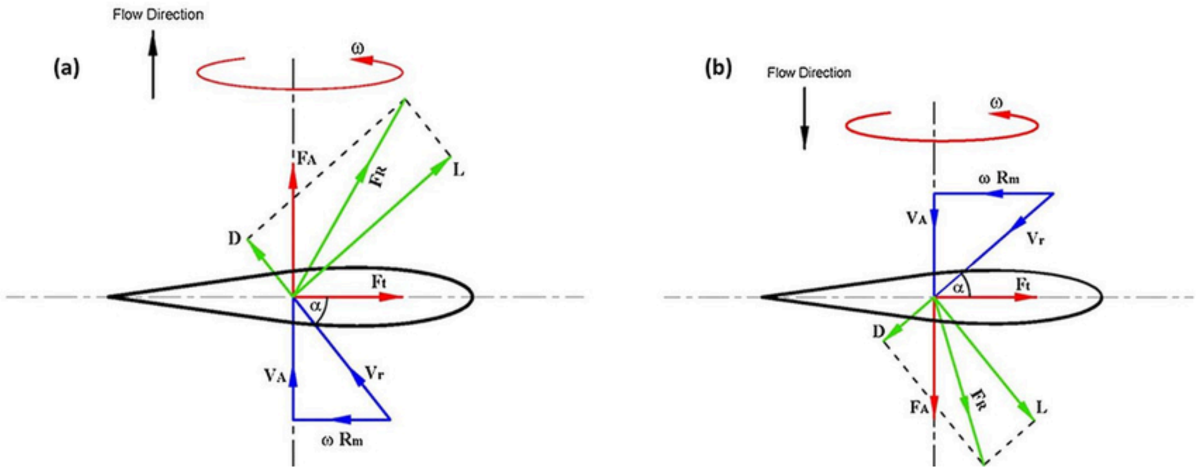


Figure 3-21: Airfoil force analysis.

Chapter Four

EXPERIMENTAL ANALYSIS

Chapter Four

4. EXPERIMENTAL ANALYSIS

4.1 EXPERMENTAL METHDOLOGY

The methodology followed in this experiment is to increase the efficiency of the wave energy system to produce more electrical energy by increasing the air speed in the oscillating water column by changing the gate angle and length.

To increase the efficiency of the system methodology has to be followed from the design and selection of system components to the conduction of the experiment, taking the measurements and interpreting the results.

4.2 PROCJECT COMPONENTS

4.2.1 Wave Generator

The tank measures 12 m in length with a width of 30 cm and is equipped with a piston type wave maker and a plane sloping beach

Figure 4-1: Plane Sloping Beach.

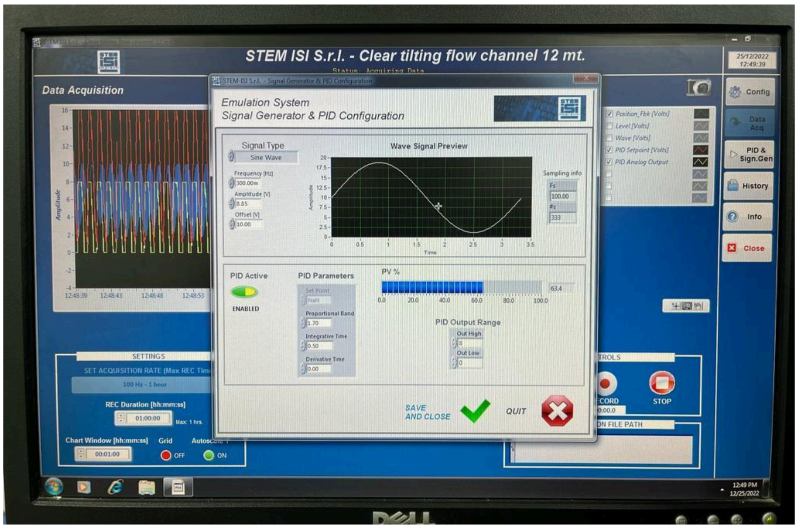


Figure 4-2: The programme that generated the wave.

4.2.2 OWC'S Chamber

Figure 4-3: Foam chamber.

Foam thickness = 5 cm	Water depth = 28 cm
Chamber length = 20 cm	Vent diameter = 2mm (2 cm from rear wall)
Chamber height = 42.5 cm	Gate height = 15 cm & 19 cm
Chamber width = 30 cm	Gate draught = 5 cm & 19 cm

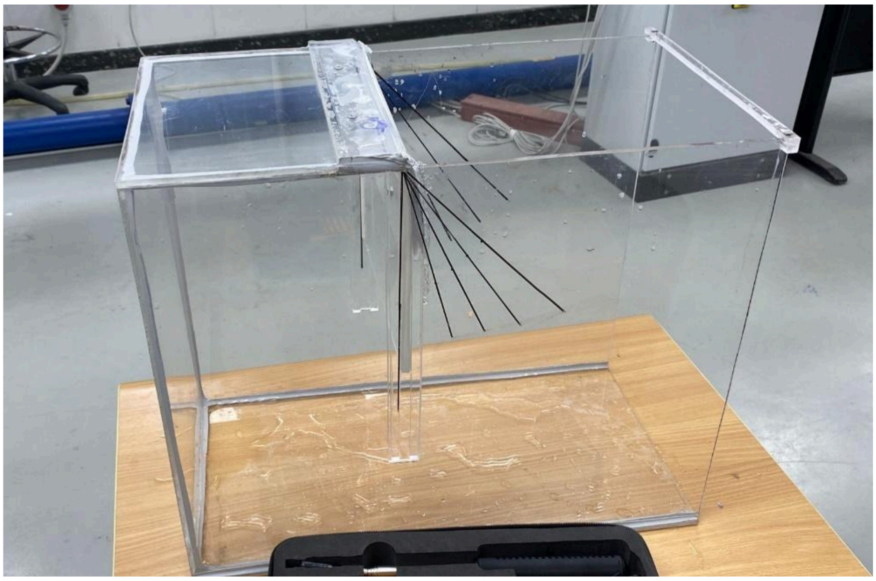


Figure 4-4: Acrylic chamber.

Acrylic thickness = 0.5 cm	Water depth = 28 cm
Chamber length = 20 cm	Vent length = 2 mm (2cm from rear wall)
Chamber height = 40.5 cm	Gate height = 15 cm
Chamber width = 28 cm	Gate draught = 5 cm

4.2.3 Wind Speed Sensor

we measured the wind speed that will be delivered to the well's turbine through the vent using a hot wire anemometer (GM8903).

Figure 4-5: Hot Wire Anemometer (GM8903).

Specifications:

- Power supply: AAA 1.5V Alkaline battery *4.
- Low battery indicating :4V±0.2V.
- Stand by current 0uA.
- Operating Current ≤60mA.
- Battery use life :20H (Continuous Use).
- Table 4-1: Wind Velocity Range:

Unit	Wind Velocity	Resolution	Lowest Point of start value	Accuracy
m/s	0.0-30.0	0.001	0.3	±3%±0.1
Ft/min	0.0-5860	0.01/0.1/1	60	±3%±20
Knots	0.0-55.0	0.01/0.01	0.6	±3%±0.2
Km/h	0.0-90.0	0.001	1.0	±3%±0.4
Mph	0.0-65	0.001/0.01	0.7	±3%±0.2

- Wind flow range：

CMM:0-999900m^3/min

CFM：0-999900 ft^3 /min

4.3 EXPERIMENT STEPS

1. put oscillating water column in the tank.
2. fill tank by water until reach height 28 cm.
3. turn on the wave generator device.
4. 4-change the frequency of wave from computer to 300Hz.
5. take the readings of the air speed from the sensor at 90-degree gate.
6. change the angle of the gate to 15-degree and take readings.
7. change the angle of the gate to 25-degree and take readings
8. change the angle of the gate to 35-degree and take readings.
9. change the angle of the gate to 45-degree and take readings.

4.4 EERIMENTS

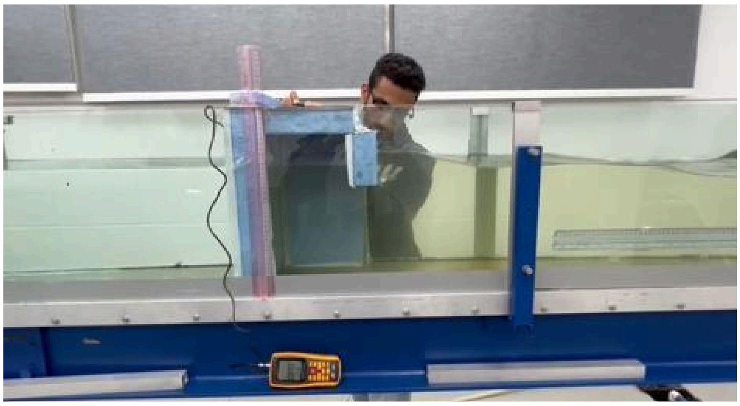
4.4.1 Fist Experiment

We used foam material for the OWC chamber in the initial experiment, but we were unable to obtain results due to water and air leakage.

4.4.2 Second Experiment

This time, we also used foam material for the OWC chamber, and we were able to obtain results.

Readings were taken for the wave frequency at 100 Hz, gate height at 15 cm, and gate angle at 90 degrees.



Air speed					Avg. Air speed
0.85	8.44	0.71	8.67	1.03	3.94

4.4.3 Third Experiment

We also used foam material for the OWC chamber, and we were able to obtain results.

Readings were taken for different frequency, gate height at 15 cm, and gate angle at 90 degrees.

Wave Frequency	Avg. Air Speed
100 Hz	0.6425
200 Hz	4.23
300 Hz	4.517
400 Hz	3.53
500 Hz	2.078

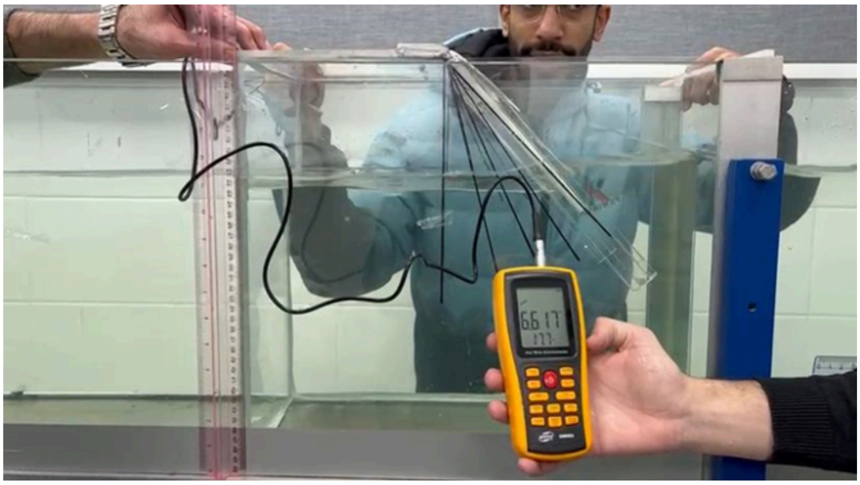
4.4.4 Fourth Experiment

We also used foam material for the OWC chamber but, this time we changed the gate height to 19cm, and the readings were taken at 90 degrees.

Wave Frequency	Air Speed
100 Hz	0.621
300 Hz	1.336

4.4.5 Fifth Experiment

We also used acrylic material for the OWC chamber, and we were able to obtain results, and the readings were taken for gate height at 15cm, and wave frequency at 300Hz.



Gate Angle	Air Speed						Avg. Air Speed
90	4.9	3.3	2.1	5.6	7.9	5.9	4.96
15	5.1	5.4	4.9	3.4	4.1	5.3	4.7
25	4.5	5.4	2.9	7.3	5.9	7.4	5.5
35	6.5	4.8	5.2	4.6	6.0	7.9	5.8
45	6.3	7.3	7.2	6.6	6.7	6.4	6.75

Conclusion

Renewable energy stands in contrast to fossil fuels. Renewable energy is energy derived from natural sources that are replenished at a higher rate than they are consumed that makes it more efficient than fossil fuels. Sunlight, wave, geothermal and wind, for example, are such sources that are constantly being replenished.

Fossil fuels - coal, oil and gas - on the other hand, are non-renewable resources that take hundreds of millions of years to form. Fossil fuels, when burned to produce energy, cause harmful greenhouse gas emissions, such as carbon dioxide.

Renewables are lower cost, environmentally friendly and healthy and generate three times more jobs than fossil fuels.

Wave energy one of the most important resources of renewable energy Wave energy is unique because it is the most concentrated form of renewable energy on earth, with power density much higher than that of wind and solar energy. Not to mention, it is also more predictable and consistent than wind or solar

And after several experiments and making the tests on 5 cases of various gate angles and wave frequencies, we concluded that average highest speed will be 6.75m/s at gate length 15cm and 45-degree angle.

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